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The impact of extreme flood and drought events on the population dynamics of *Scrobicularia plana* (Da Costa)

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

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Resumo

Os ambientes marinhos estão entre os ecossistemas mais importantes do planeta, tanto em termos ecológicos como sócio-económicos. O estuário do Mondego, como muitos outros, providencia funções ecológicas essenciais, serviços e óptimos habitats para muitas espécies e possui extrema importância para a população humana local. Todos estes benefícios oferecidos por este ecossistema podem estar em risco, visto que a frequência e a intensidade de eventos climáticos extremos, tais como cheias e secas, tem vindo a aumentar drasticamente nas últimas décadas, como resultado das alterações climáticas. Estas perturbações afectam a qualidade geral do estuário, diminuindo a sua produtividade através de impactos na abundância e biomassa das populações e comunidades. O objectivo principal deste estudo foi analisar a resposta de *Scrobicularia plana*, uma espécie dominante de bivalves na comunidade macrobentónica do Mondego, à forte cheia de 2000/2001 e à seca extrema de 2004/2005. Esta espécie foi altamente afectada por estes dois eventos, mas de diferentes modos. A cheia provocou uma total ausência de recrutamentos em 2001, a diminuição da biomassa e alterou a estrutura da população. A seca causou um maior impacto na biomassa, o declínio na abundância geral e também alterou a estrutura da população. A variação da salinidade da água no estuário está directamente relacionada com a quantidade de precipitação. Os valores extremos de salinidade alcançados durante as cheias e as secas são uma das principais razões para a alteração da dinâmica populacional de *Scrobicularia plana*. Tendo esta espécie uma extrema importância ecológica e económica, os eventos extremos climáticos causaram grandes impactos ecológicos e económicos na área em questão.

Abstract

Marine environments are among the most important ecosystems in the world, ecologically and socio-economically. Mondego estuary, as many others, provides essential ecological functions, services and great habitat for many species and is of a huge importance for local human population, due to their dependence on its resources. All these goods offered by this ecosystem may be at risk as the frequency and intensity of extreme weather events, such as floods and droughts, has been drastically increasing in the last decades, as a result of the global climate change. These stressors affect the general quality of the estuary, decreasing its productivity through impacts on the abundance, biomass and fitness of individuals, populations and communities. The main goal of this study was to analyse the response of *Scrobicularia plana*, a deposit-feeder bivalve, dominant species in Mondego's macrobenthic community to the extreme flood of 2000/2001 and to the severe drought of 2004/2005. This species was highly affected by both events, but in different ways. Flooding caused a total absent of recruitments in 2001, a decrement in biomass and changed the population structure, while drought caused bigger impact in biomass and declined the general abundance, also changing the population structure. The variation of water salinity in the estuary is in direct relation to the amount of precipitation. Reaching extreme lower and high values of salinity during floods and droughts is one of the principal causes to the decrement of population dynamics of *Scrobicularia plana*. As this species has an extreme ecological and economical importance to the estuary and to human population, extreme climate events caused direct and indirect impacts, in the area.

Contents

1. Introduction

Introduction

Coastal zone ecosystems are among the most important environments on Earth ecologically and socio-economically with an estimated value of ~ US$ 15-20 trillion y^{-1} globally (Hays et al., 2005; Harley et al., 2006; Cardoso et al., 2008b). They are highly productive natural ecosystems and provide essential ecological functions and services for migratory and resident species (Paerl, 2006; Dolbeth et al., 2007) and they also have a huge importance to several human activities, providing many important resources to mankind such as food production, nutrient storage and recycling, gas regulation and recreation (Hays et al., 2005; Harley et al., 2006; Cardoso et al., 2008b). Moreover, they are also highly appreciated areas either to live or for recreation and tourism (van der Meulen et al., 2004; Martínez et al., 2007). The vast opportunities given by these areas have historically attracted the humans and highly dense populations have been settling on the proximity of the ocean and riverbeds, using them as essential navigation and transport routes and developing important urban, industrial and commercial centres, and many of the major cities in the world are nowadays located on coastal areas (Martínez et al., 2007).

Estuaries are semi enclosed coastal ecosystems, constituting a transition area where fresh water from rivers mixes with saline water from oceans and are characterized by high daily variations on temperature, water circulation, salinity and oxygen conditions exposing its inhabitants to great physiological stress (Mclusky and Elliot, 2004; Neill, 2005). Still, estuaries are highly productive biomes (Mclusky and Elliot, 2004; Dolbeth et al., 2007). They receive nutrient inputs from fresh and marine water and function as filters for particulate matter, contributing for nutrient cycling and flux regulation of water, particles and pollutants, providing abundant food resources for the entire trophic web (Elliot et al., 2002; Mclusky and Elliot, 2004; Dolbeth et al., 2007). Several communities of plants and animals (invertebrates, fishes and birds) depend on estuaries for habitat conditions, food supply, shelter and protection using them as nursery grounds and migratory routes (Cardoso et al., 2005; Verdelhos et al., 2005; Dolbeth et al., 2007; Elliot et al., 2002; Leitão et al., 2007; Martinho et al., 2007; Mclusky and Elliot, 2004; Lopes et al., 2006). Moreover, they are also considered as strategic locations for humans that use them as natural transport routes, recreation facilities and food source for developing fish or shellfish cultures, agriculture fields and industry, representing a very important economic resource (Kennish, 2002; Mclusky and Elliot, 2004; Martínez et al., 2007; Svensson et al., 2007; Vasconcelos et al., 2007).

Global warming is one of the major environmental problems the world is facing, causing increased temperature and climate variability. Anthropogenic activities, such as industry, combustion of fossil fuels and widespread deforestation have been contributing to an increase in the atmospheric concentration of the main greenhouse gases accelerating the natural warming of the Earth's surface (Short and Neckles, 1999; Simas et al., 2001; Epstein and Mills, 2005; Houghton, 2005; Harley et al., 2006). This will cause a global increment in air and water temperature, melting of snow and ice widespread, sea level rise and increased extreme climate events such as floods, droughts and heat waves (Short and Neckles, 1999; Simas et al., 2001; Houghton, 2005). Climate change will result in severe impacts on a large variety of organisms and natural ecosystems affecting their composition, function, biodiversity and productivity (Short and Neckles, 1999; Simas et al., 2001; Adams, 2005; Harley et al., 2006; Paerl, 2006; Cardoso et al., 2008a). These impacts are defined as changes that have deleterious effects on ecosystems, socioeconomic systems and on human and animal welfare (United Nations, 1994). Entire ecosystems, when subjected to climate changes, may be disrupted as a consequence of differences in response times of species (IPCCWGI, 2001). A few studies have been conducted on the impact of large-scale weather events, such as floods and droughts, on the macrobenthic communities, confirming that these events may have implications for the ecosystem functioning (Cardoso et al., 2008b). It is then extremely necessary to conduct work to understand the wide complexity of the climate change problem and studies on population and community level processes are thus required to know how an ecosystem responds to global climate change.

The Mondego estuary is a small estuary of 8.6 km^2, located in a warm temperate region on Southwest Europe on the Atlantic coast of Portugal (40°08'N, 8°50'E), near Figueira da Foz. This is a very important estuary for the local human populations, which explore its natural resources (Cardoso et al., 2008b). It is the location of an important mercantile harbour and a recreational marina (Ribeiro, 2001). Industry, aquaculture and agriculture are expanding considerably in its area.

This estuary has been suffering with the human activities through the last 20 years, causing huge ecological pressures, either physical (regularization of navigation channels; construction of channels and dams to support industry and agriculture; construction of new facilities) or chemical (discharges of organic nutrients an pollutants from urban waste sewage, agricultural, aquaculture and industrial activities), which leads to changes on the river hydrodynamics and topography, and on increased water turbidity and concentration of growth limiting nutrients - eutrophication. This process which Mondego estuary has been experiencing since the late 1980's has caused serious biological changes leading to a progressive replacement of seagrass bed of *Zostera noltii* by opportunistic macroalgae (Marques et al., 2003; Pardal et al., 2004; Cardoso et al., 2005, 2008a; Verdelhos et al., 2005). As a result, *Z. noltii* beds declined from an extent of 15 ha in the early 1980's to 0.02 ha in the mid 1990's (Pardal et al., 2004), leading to a shift in primary producers from *Z. noltii* towards faster growing green macroalgae, which affected population dynamics and production of key species impoverishing the entire community (Cardoso et al., 2005, 2008a; Verdelhos et al., 2005; Dolbeth et al., 2007).

To stop this tendency, a management plan was implemented in 1998 in this estuary. In order to restore the seagrass bed, the measures taken were to decrease the nutrient loading, to improve the water circulation and to protect *Z. noltii* beds (Cardoso et al., 2005, 2007; Lillebø et al., 2005; Verdelhos et al., Dolbeth et al., 2007). This management plan had positive results on the restoration of the ecosystem (Cardoso et al., 2005, 2007; Lillebø et al., 2005; Verdelhos et al., 2005; Dolbeth et al., 2007), with a gradual *Zostera noltii* recovery in biomass and extent, and showing a good influence on macrofaunal key species and on the whole community.

During the ongoing recovery process, unprecedented extreme climate events affected severely the Mondego estuary, re-setting the recovery process (Cardoso et al., 2008b). In fact, over the last decades the climate in Portugal has been changing, compared to the general climate patterns for the period 1931-1990, occurring more frequent and intense extreme climate events (INAG - Portuguese Water Institute, http://snirh.inag.pt/ and IM - Portuguese Weather Institute, http://web.meteo.pt/pt/clima/clima.jsp). Mean air temperature rose progressively (from 1931 to 2005: + 0.15℃ per decade) and some of the hottest years ever occurred. Moreover, the frequency and intensity of heavy rainfall and low precipitation drought events increased (Cardoso et al., 2008a). The most extreme events registered in the Mondego estuary during the last decades were a huge flood in the winter 2000/01 reaching unprecedented high values of precipitation, especially for central Portugal (2000/01: 1802.1 mm against a mean annual value for 1940 to 1997: 1030.6 mm), followed by gradual occurrence of a drought starting in 2004 and attaining a severe drought in 2005 (2005: 486.1 mm against the mean annual of 1030.6 mm). As this estuary has an extreme importance to the local human populations, any effects in its ecological condition caused by natural and anthropogenic stressors through single, cumulative and synergistic processes, should highly affect those human populations (Vinebrooke et al., 2004; Adams, 2005; Cardoso et al., 2005, 2008a; Dolbeth et al., 2007). Thus it is a key issue to understand how these ecosystems respond to natural climate and anthropogenic stressors.

The bivalve *Scrobicularia plana* is one of the most important species in the Mondego estuary with a high economic value to the local human population and is a key species in the macrobenthic community, which is an essential part of the ecosystem in terms of its ecological dynamics and production (Verdelhos et al., 2005; Dolbeth et al., 2007; Cardoso et al., 2008b). It is a long-lived deposit-feeding bivalve species living buried in muddy to sandy sediments (Hughes, 1970; Guelorget and Mazoyer-Mayére, 1983; Essink et al., 1991; Sola, 1997; Guerreiro, 1998; Casagranda and Boudouresque, 2005; Verdelhos et al., 2005). It is distributed from Norwegian Sea to Senegal including the Mediterranean, inhabiting intertidal coastal waters being very abundant and is often the dominant species of shallow water benthic communities (Hughes, 1970; Guelorget and Mazoyer-Mayére, 1983; Essink et al., 1991; Sola, 1997; Guerreiro, 1998; Casagranda and Boudouresque, 2005; Verdelhos et al., 2005). It is tolerant to a wide range of physical and chemical conditions, changes in the sediment and rapid demographic adaptability to variations in the environment (Hughes, 1970; Casagranda and Boudouresque, 2005).

The main goal of this study is to assess the response of the *Scrobicularia plana* population in the Mondego estuary, facing the occurrence of extreme climate events – a severe flooding in 2000/2001 and an intense drought during 2004 and 2005, analysing the impacts on population dynamics, structure and production.

2. Materials and Methods

2.1. Study site

The Mondego estuary is located in a warm temperate region, on the western coast of Portugal (40º08'N, 8º50'W). It is a small estuary of 6.8 km^2, and it comprises a northern and a southern arm, separated by Murraceira Island.

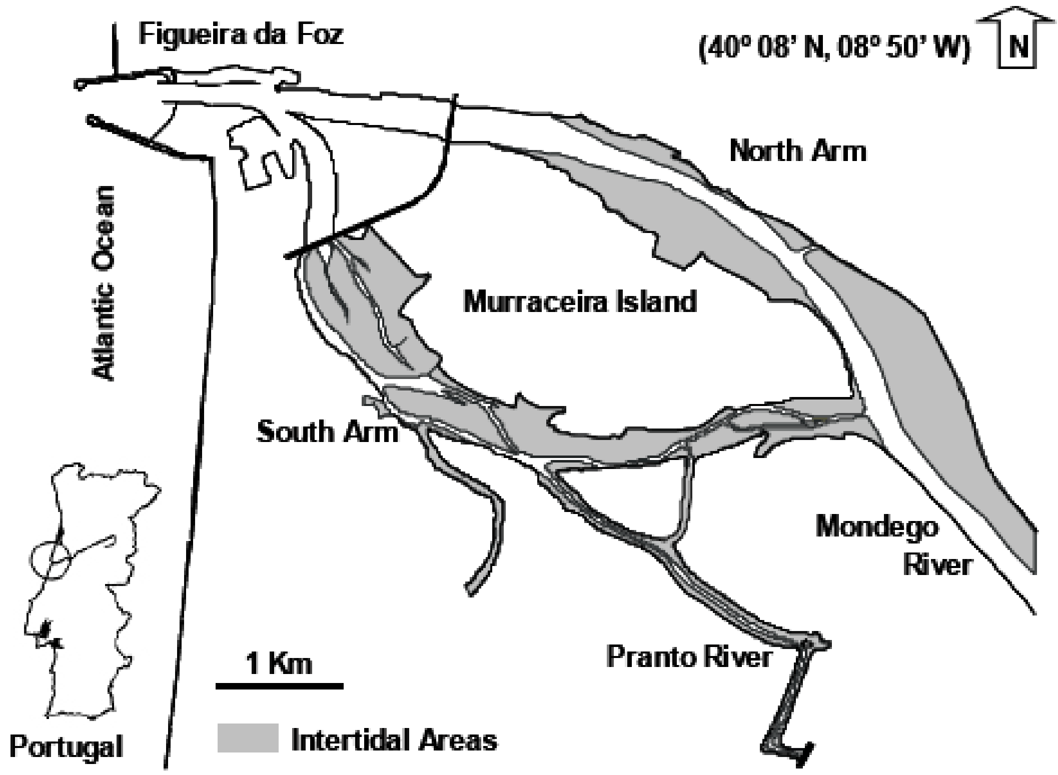


Fig. 1 - The Mondego estuary.

The North arm is deeper (4-8 m during high tide, tidal range 1-3 m), highly hydrodynamic providing the mains navigation channel and the location of the Figueira da Foz harbour. The South arm is shallower (2-4 m during high tide, tidal range 1-3 m) and is characterized by large areas of exposed intertidal flats during low tide. Until 1998, the South arm was almost silted up in the innermost areas, and the river outflow occurred mainly through the Northern arm. Water circulation was therefore mostly dependent on the tides and on the freshwater input from Pranto River, a small tributary with a flow controlled by a sluice, which was regulated according to the water level of rice fields in the Mondego valley. In the early 1980's, this sub-system showed an extended *Zostera noltii* coverage, however, as the eutrophication increased, seagrass declined progressively. In 1998 a restoration intervention improved water circulation and transparency and decreased nutrient loading, in order to mitigate the eutrophication effects, leading to a gradual ecosystem recovery. Three different sampling sites were established in the Southern arm: a) *Zostera noltti* beds, a non-eutrophic area located downstream; b) Intermediate area, adjacent to the previous, with no seagrass cover until 2001, however, due to the management plan implementation, this area has been progressively re-occupied by *Z. noltti*; c) eutrophic area, in the inner part of the estuary, characterized by the absence of rooted macrophytes (for more than 20 years) and now covered seasonally by green macroalgae.

2.2. Field programme and laboratory procedures

Sampling was carried out in the three areas from January 2000 to December 2001 and from January 2004 to December 2005. During this period, samples were collected in the morning during low tide, monthly. Six sediment cores with a sectional area of 141 cm^2 each were randomly taken to a depth of

25 cm, by using a manual corer. Each sample was washed in estuarine water over a 500 µm mesh sieve, placed into plastic bottles and preserved in 4% buffered formalin. At each sampling station, water temperature and salinity were measured directly in situ in low water pools.

2.3. Scrobicularia plana

S. plana individuals were counted and their total length measured. Length-weight relationships were determined for production estimates. Preliminary ANOVA of length x ash free dry weight (AFDW) relationships indicated no significant seasonal differences and an overall regression equation was used (AFDW = 0.00000991 x Total length 2.68809, r^2 = 0.97, N = 152). The (AFDW) of each of the individuals used for the regression equations was assessed after combustion for 8 h at 450º C.

Annual production was estimated upon cohort recognition, determining growth increments or net production (P) as described in Dauvin (1986), Cardoso et al. (2005) and Verdelhos et al. (2005).

Percentage of biomass loss (stock loss) during the flood and the drought was estimated. To do that, we defined the months of pre-flooding, flooding and post-flooding in 2000/2001. In each of these periods, average biomass was calculated and the difference of average biomass between each period and the next, representing the stock loss then converted into percentage. The same was made for 2004/2005, but only a pre-drought and a drought period were defined.

2.4. Climate Data

Temperature data (mean monthly temperature and climate normal temperature 1971-2000) were obtained from the Geophysical Institute of the University of Coimbra – IGUC, and rainfall data (monthly precipitation) from INAG - Soure forecast station, which were used to calculate normal precipitation (1971-2000), seasonal accumulated precipitation (e.g. Winter; Spring; Summer; Autumn) and normal seasonal accumulated precipitation (1971-2000). An analysis was also made of the available information on drought conditions, by constructing a drought index, based on a Decis - classification (http://www.meteo.pt/pt/clima/clima_seca3.html). Rainfall data are divided in 10 equal parts, delimited by 1º decil, 2º decil, and so on until the 10º decil, to provide the following classification:

Table I - Classification of years following drought index

inter-descis interval	qualitative designation
1	extremely dry
2	very dry
3,4	dry
5,6	normal
7,8	rainy
9	very rainy
10	extremely rainy

3. Results

3.1. Portugal Climate

Climate in Portugal has been changing over the last decades leading to increased and intensified climate variability over the years, with the occurrence of several extreme temperature and precipitation events. In central Portugal, annual air temperature followed different trends over the last 65 years (Fig. 2 A). Temperature decreased from the 1940's to 1970's and then started to increase from mid 1970's maintaining this trend to present date, following the global warming tendency.

Analysis of the seasonal accumulated precipitation pattern for the last 65 years, compared to climate normal of 1971-2000 (IM – Portuguese Weather Institute, http://web.meteo.pt) showed several rainfall events above the mean winter precipitation for the period 1971-2000 (Fig. 2 B). In fact floods, here defined as precipitation in excess of 50% of the mean value, have clearly increased of frequency during the last 30 years (Fig. 2 C). Between 1940 and the mid 1960's no flooding events were recorded, but since then its frequency has increased substantially. The unprecedented high value of 796 mm was reached on the winter of 2001, causing the largest flood of the 20th century (INAG – http://snirh.inag.pt).

Finally, the frequency and intensity of dry years has also increased during the last 35 years (1970 – 2005), compared to the previous 65 years (1940 – 2005) (Fig. 2 D). Between 1940 and 1970, 1 extremely dry year, 1 very dry year and 6 dry years occurred, while from 1970 to 2005 were registered 2 extremely dry years, 2 very dry years and 11 dry years.

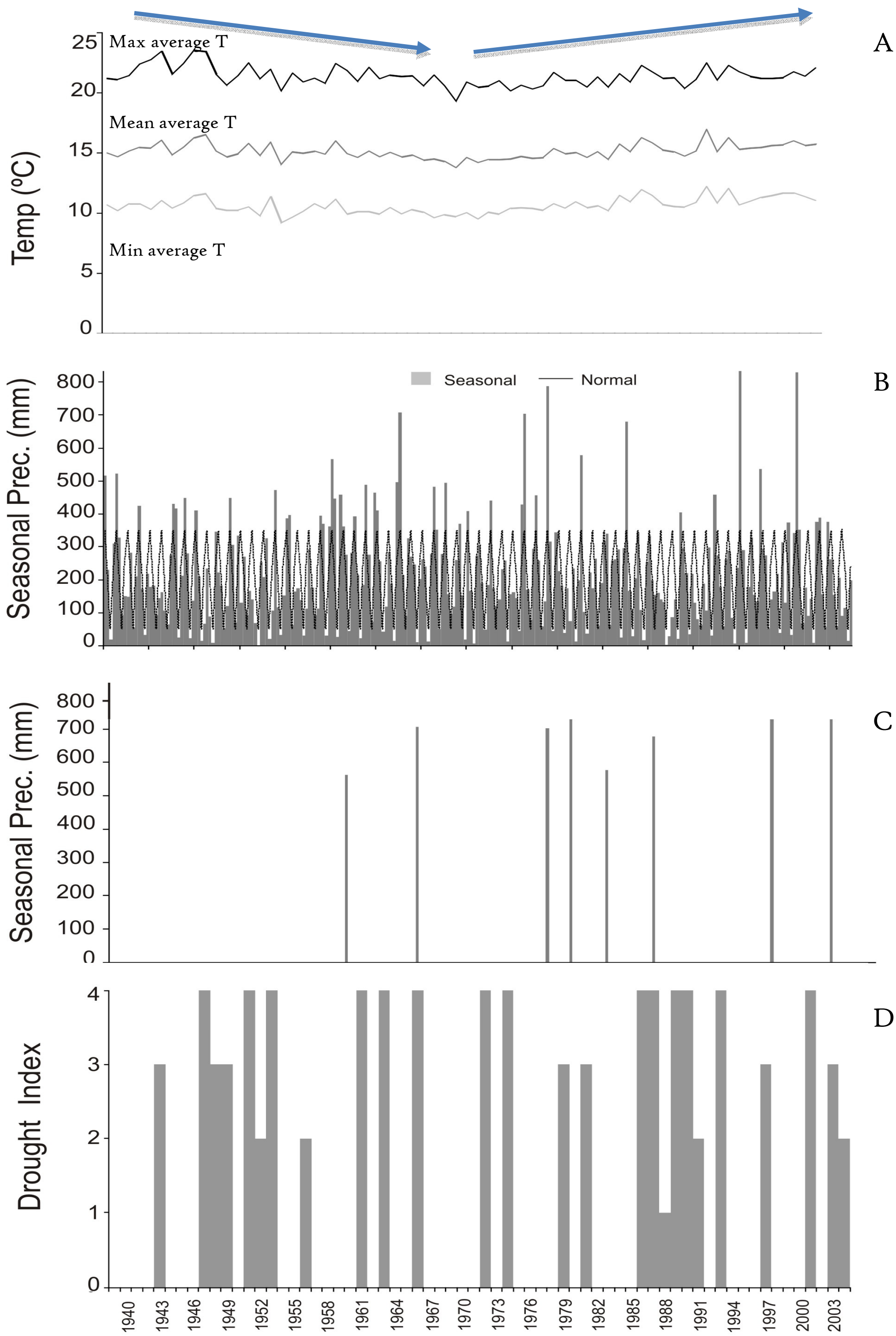


Fig. 2 - Climate variation in Portugal from 1940 until 2005: A) air temperature; B) seasonal accumulated precipitation compared to normal precipitation 1971-2000; C) floods; D) drought years.

3.2. Mondego estuary climate

The Mondego estuary is a warm temperate coastal system with a typically Mediterranean temperate climate, showing a clear annual seasonality considering the air and the water temperature during 2000/2001 (Fig. 3 A) and 2004/2005 (Fig. 3 B), with higher values of temperature in the summer and lower values in the winter for both, air and water temperature.

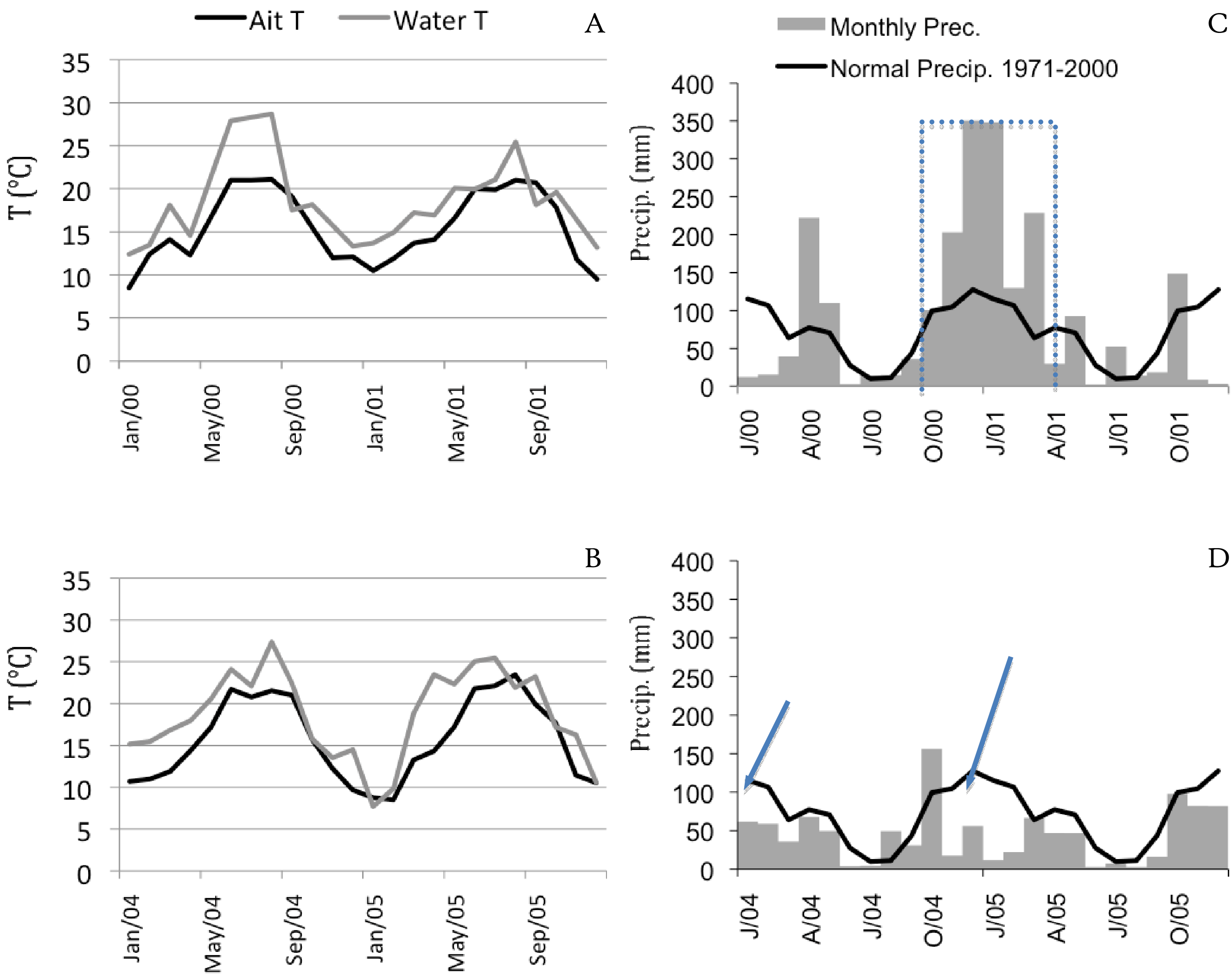
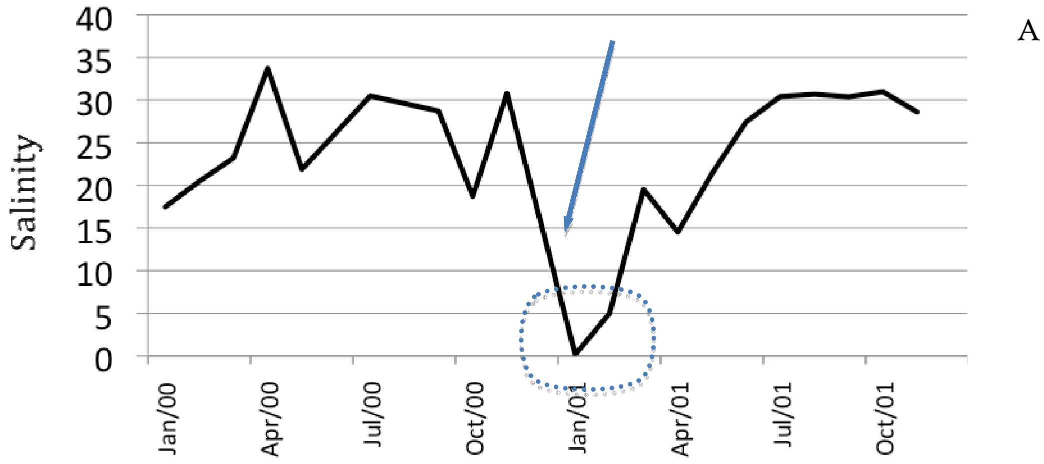


Fig. 3 - Climate in the Mondego estuary in 2000/2001 and in 2004/2005: A) air and water temperature in 2000/2001; B) air and water temperature in 2004/2005; C) monthly precipitation in 2000/2001 compared to normal precipitation in 1971-2000; D) monthly precipitation in 2004/2005 compared to normal precipitation in 1971-2000.



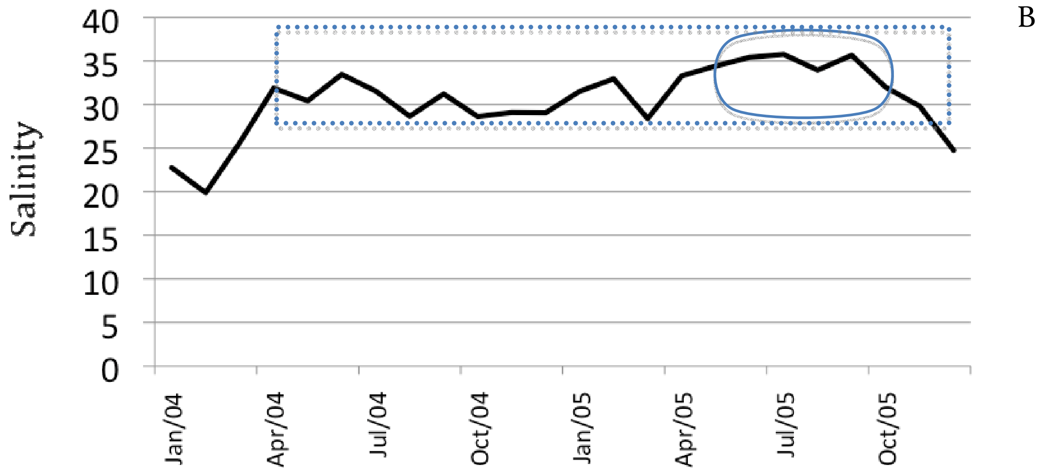
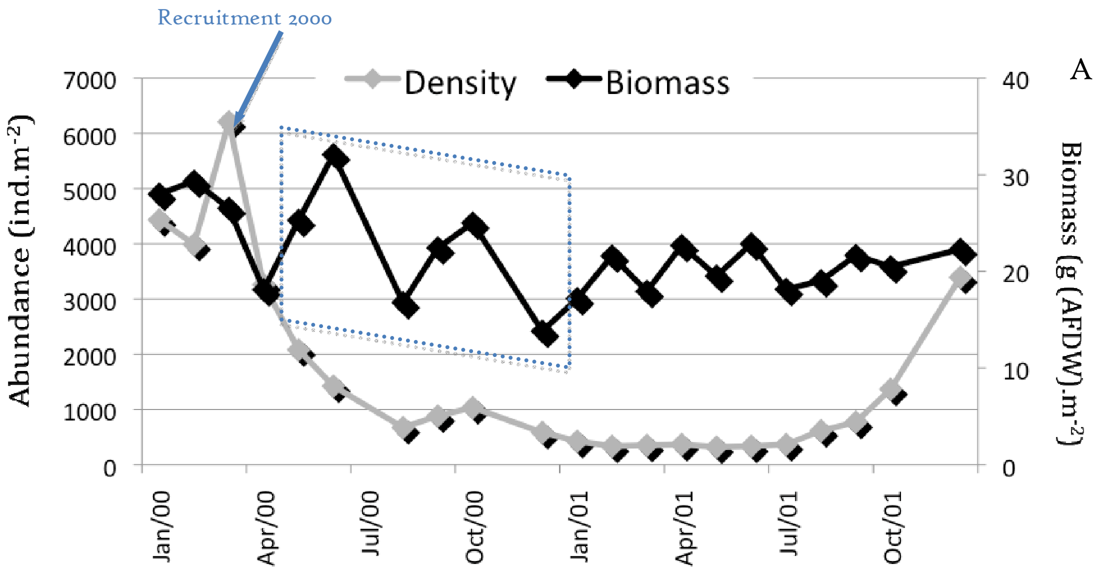


Fig. 4 - Variation of the water salinity in the sampling areas of the Mondego estuary. A) 2000/2001; B) 2000/2001.

Monthly precipitation also follows a seasonal pattern, but in 2004/2005 it is not so clear (Fig. 3 D). In comparison to the precipitation regime with mean rainfall pattern for the centre of Portugal for the period of 1971-2000 (winter: 352 mm, spring: 253 mm, summer: 48 mm, autumn: 238 mm), one above mean precipitation in the winter 2000/2001 (792 mm) is evident (Fig. 3 C). This hydrological year is particularly extreme and is characterized by the occurrence of severe flooding, particularly from October 2000 to March 2001, showing much higher values than the mean normal precipitation. In 2004 and 2005 monthly precipitation is usually lower than the mean normal (Fig. 3 D), with intense dry periods particularly during winter 2004/2005 (31.9 mm). Salinity is dependent on freshwater input and consequently is related to rainfall and flooding, following the variation of precipitation. During 2000 salinity values did not vary very much and were almost always above 20 $g.l^{-1}$ and lower than 30 $g.l^{-1}$ (Fig 4 A). The end of this year was characterised by a dramatic decline in the salinity, which is coincident with the huge flooding, reaching values close to 0 $g.l^{-1}$ in January/2001. Afterwards, it started to increase, reaching values around 30 $g.l^{-1}$ in the summer. In the period of 2004/2005 the water salinity never experienced significant declines (Fig. 4 B). From February/2004 to May/2004 there was an increase in the salinity reaching values above 30 $g.l^{-1}$ and it kept above this value for almost the whole period until the end of 2005. In the summer of 2005 it even reached values above 35 $g.l^{-1}$ which is close to salinity of seawater.

3.3. Density and Biomass

Scrobicularia plana abundance and biomass evolved differently during the flooding of 2000/2001 and in the severe drought of 2004/2005, but both had a negative impact in the population. During 2000/2001 biomass presented a decline from about 30 $g(AFDW).m^{-2}$ to 15 $g(AFDW).m^{-2}$ (Fig. 5 A) from July/2000 until about January/2001 and then remained constant for the rest of the year. *Scrobicularia plana* density for the same years revealed abundance



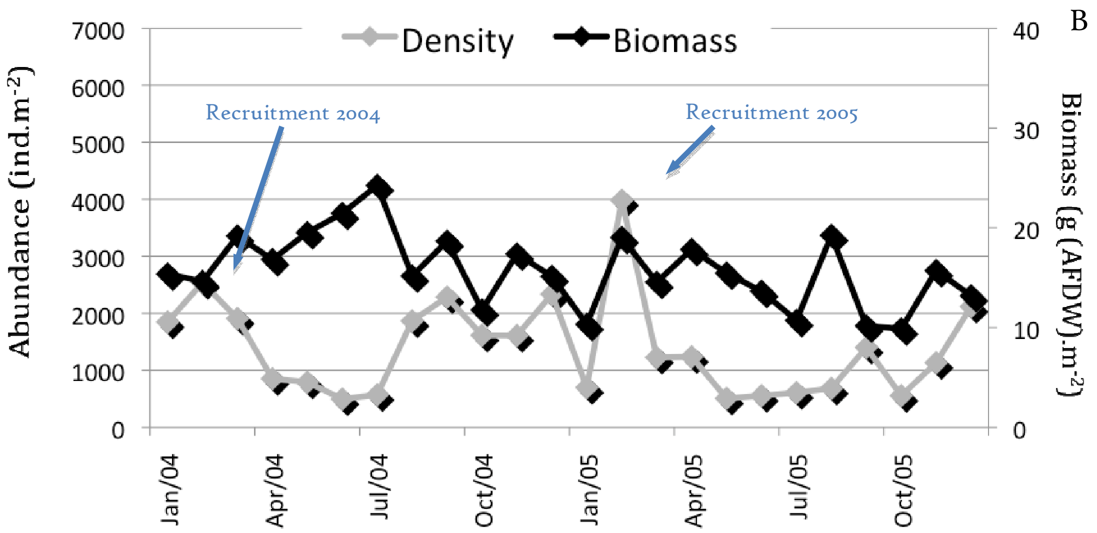


Fig. 5 - Variation of density and biomass of *Scrobicularia plana* community. A) 2000/2001; B) 2004/2005.

peak in early spring of 2000, related to juveniles recruitment. However after that, density suffered a huge decline and remained in values lower than 1000 ind.m^{-2} until October/2001 when it started to recover (Fig. 5 A). During 2001 no recruitment was registered.

For the period 2004/2005 biomass of *S. plana* seems to be more affected than in 2000/2001. The analysis of the data showed that extreme drought

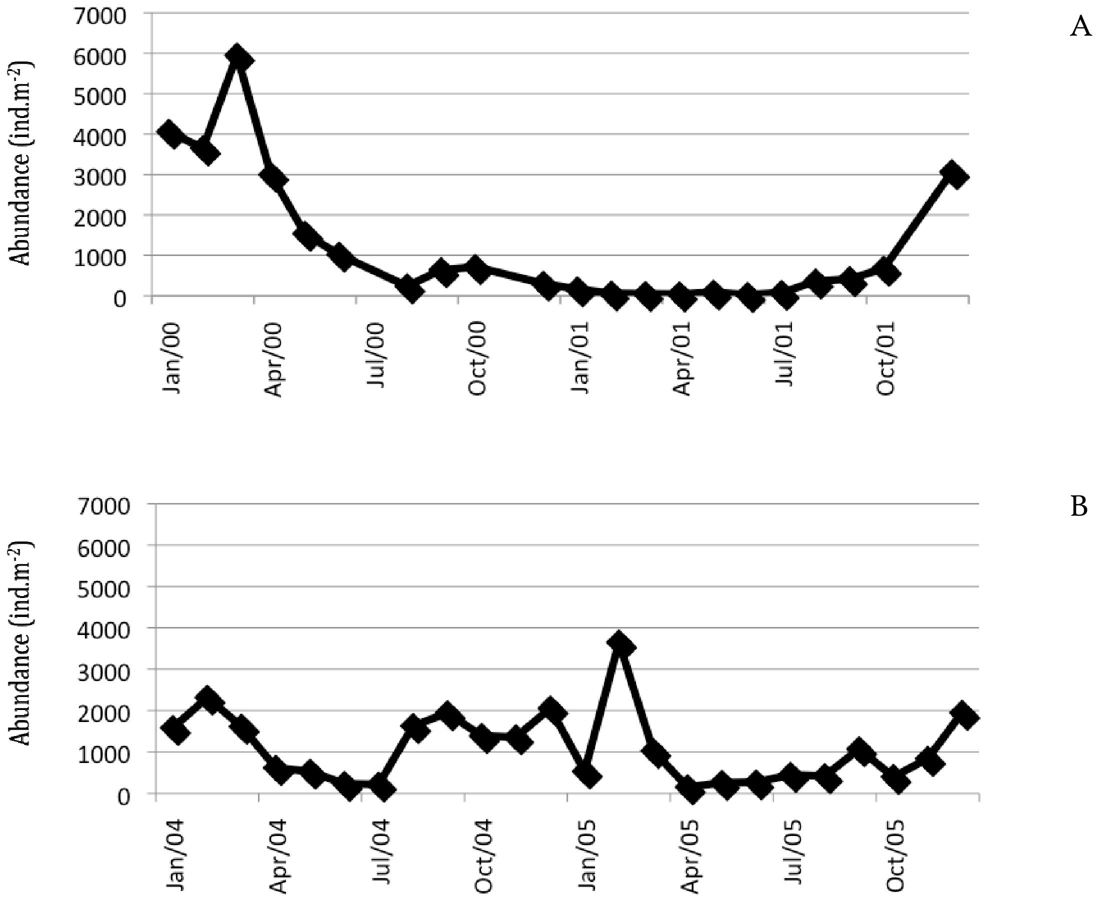


Fig. 6 - Variation of density of juveniles (<4 mm) of *Scrobicularia plana* community. A) 2000/2001; B) 2004/2005.

caused a decline of biomass from July until the end of 2005 (Fig. 5 B). Recruitments were not so affected in this time. In the Fig. 5 B we can see two peaks in the abundance corresponding to the recruitments of *S. plana* for 2004 and for 2005. Both appeared in the same time of year, which is the end of winter and beginning of spring. Density in 2004/2005 never reached the lower values of 2000/2001 and it seems to be more affected during the summer.

Concerning the abundance of juveniles, a similar pattern to the abundance of total population is registered (Fig 6). It is very clear the high recruitment peak in 2000 and the severe effect caused by extreme flood in 2001, when no recruitment occurred. Abundance values are close to 0 ind.m^{-2} during many months in this year, which are related to the occurrence of heavy rainfall and flooding events (Fig 6 A). For the period of 2004/2005 the abundance of juveniles is almost always very low, reaching higher values only in the recruitment process (Fig 6 B).

Biomass of mature adults followed the tendency of the total population, for 2000/2001 and 2004/2005. It was affected during the flood, declining in the winter 2000/2001, but it seemed to be getting stable after March/2001 (Fig. 7 A). In 2004/2005 the tendency was to decrease after July/2004 and all along the year of 2005 (Fig. 7 B).

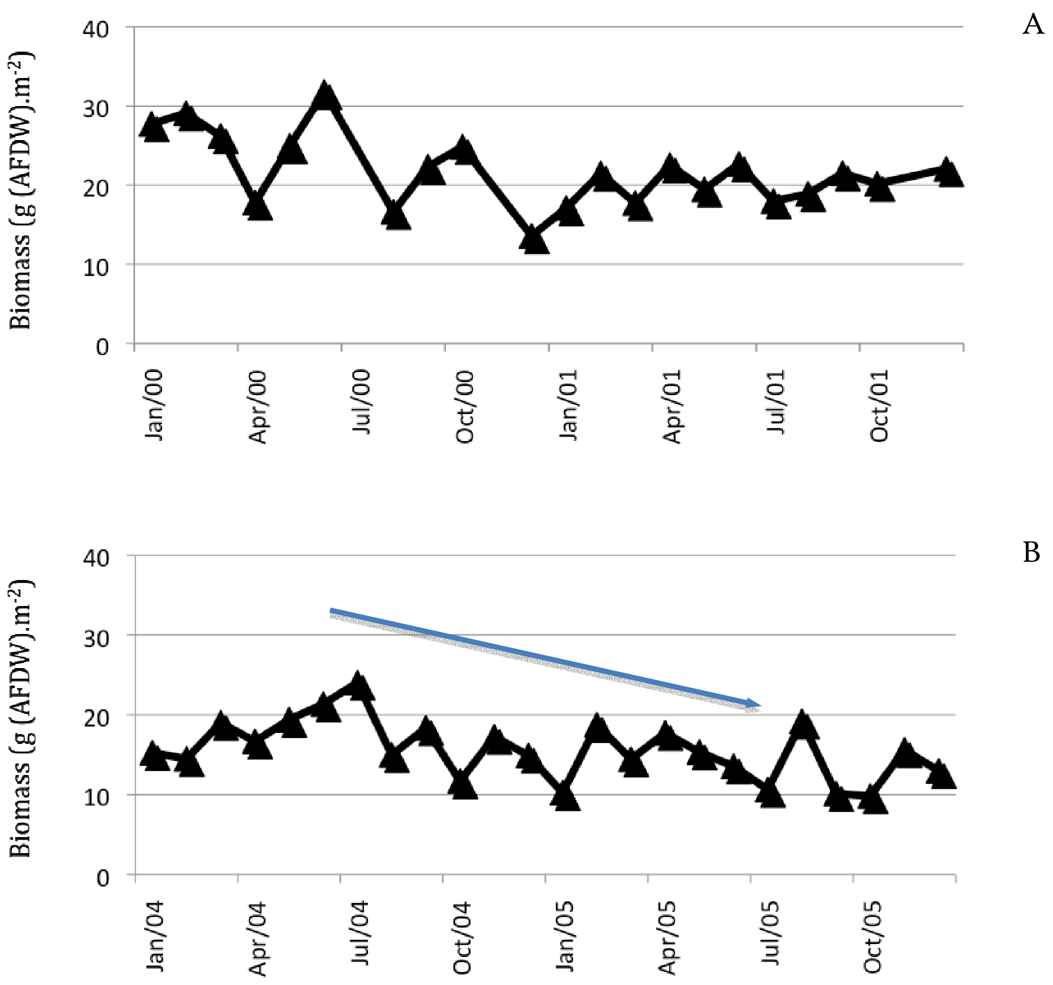


Fig. 7 – Biomass of mature adults (>20 mm) of *S. plana.* A) 2000/2001; B) 2004/2005.

3.4. Population Structure

The presence of different classes in *Scrobicularia plana* population can be seen in the winter/2000. A new cohort can be distinguished in the smaller individuals in the spring/2000, which represents the recruitment of the previous winter as the data shown begin in individuals with already 4.25 cm (Fig. 8). That cohort is no longer seen in the next seasons because of the increased mortality in the juveniles caused by the flood. During the first half of 2001 any new cohort is revealed showing the lack of recruitments (Fig. 9). The population in the spring of 2001 is very less structured. In autumn/2001 the population structure started recovering, indicating a decrease in the mortality.

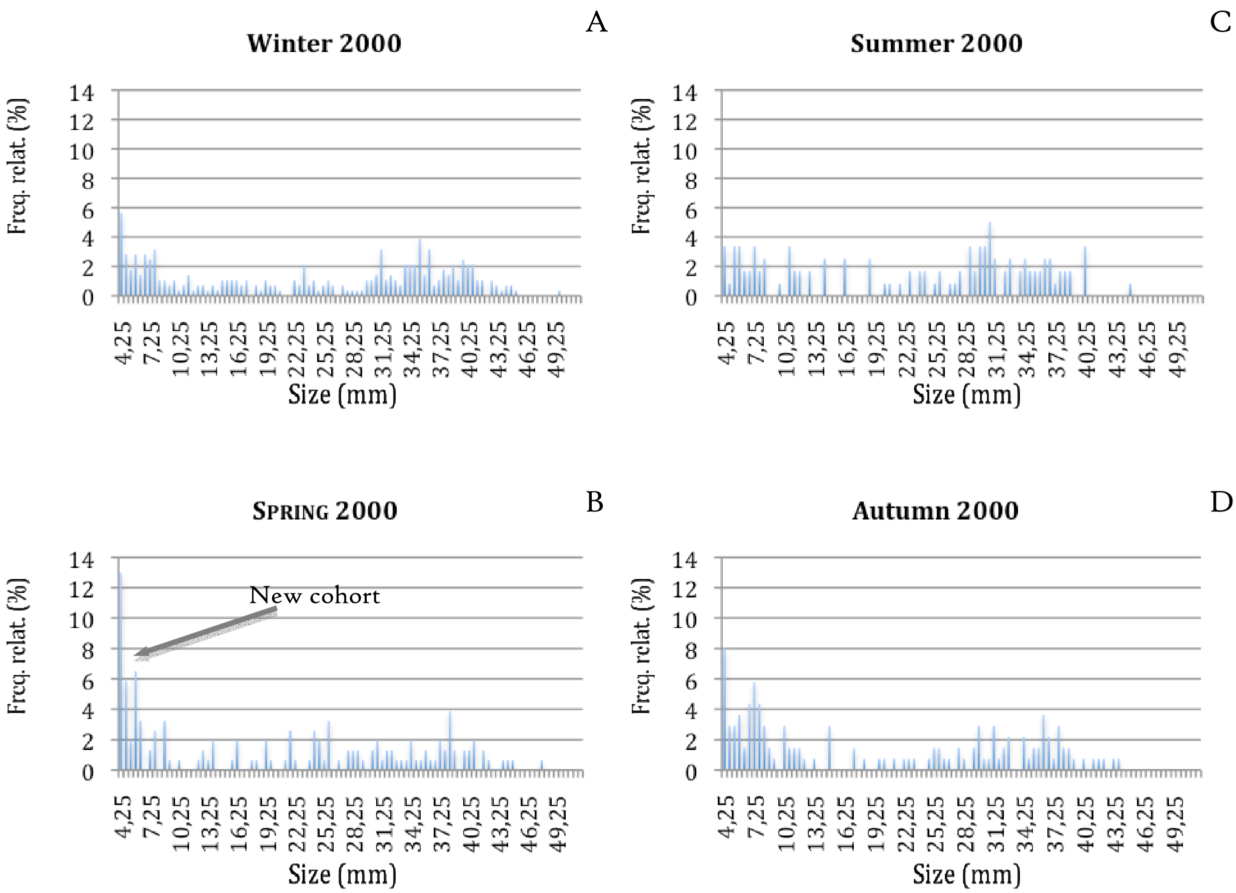


Fig. 8 - Structure of the population of *Scrobicularia plana* in 2000.

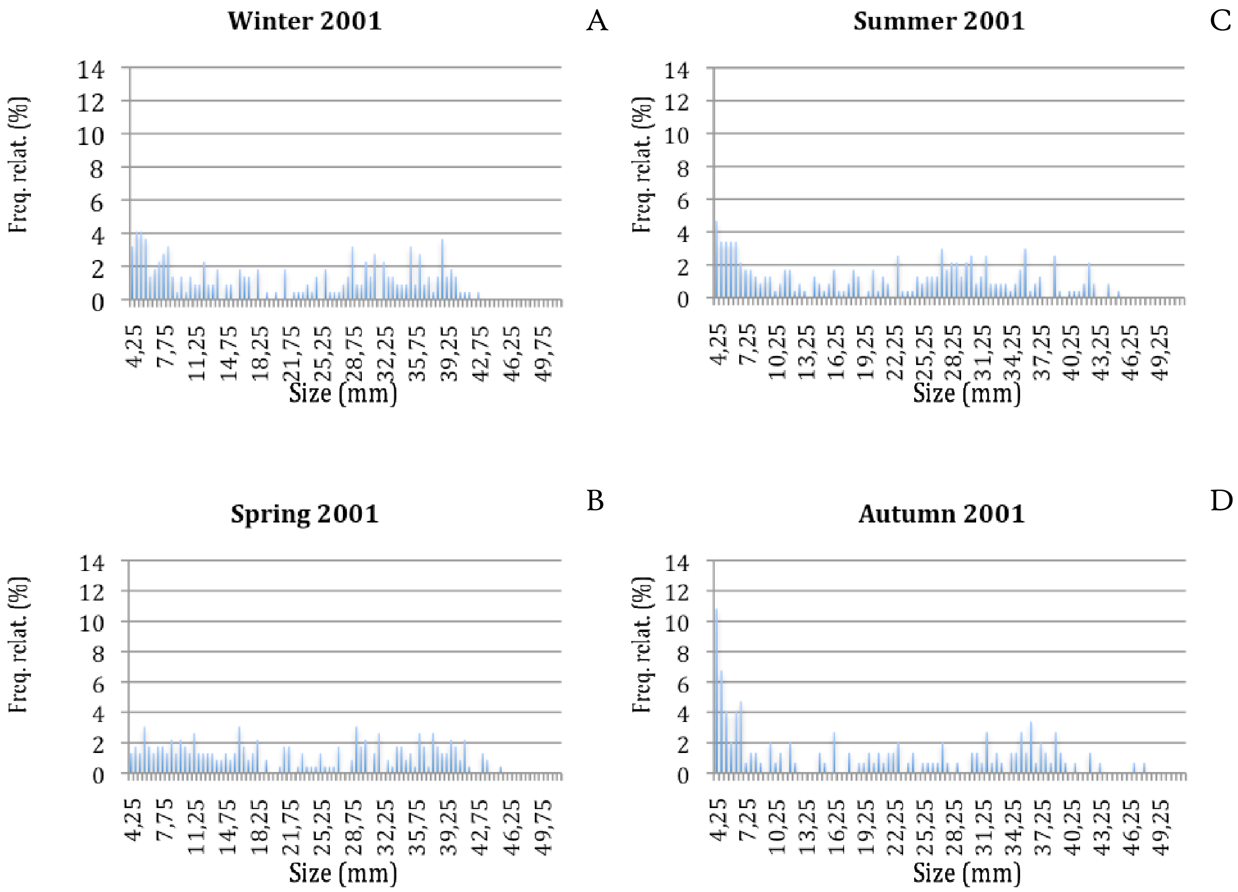


Fig. 9 - Structure of the population of *Scrobicularia plana* in 2001.

The population in 2004 is much more structured than in final of 2001 and classes can be distinguished. In the spring of the same year a new cohort is revealed, being again a recruitment from winter (Fig. 10). The last season of 2004 reveals a population much less structured, a tendency that continued along 2005. In this year a new cohort can also be seen in the spring, but this recruitment had much less individuals than the previous ones. In fact, the whole population decreased in abundance of individuals of all sizes, showing a structure without any classes in the summer and even worse in the autumn, a result of the increased mortality in the whole population caused by the severe drought (Fig. 11).

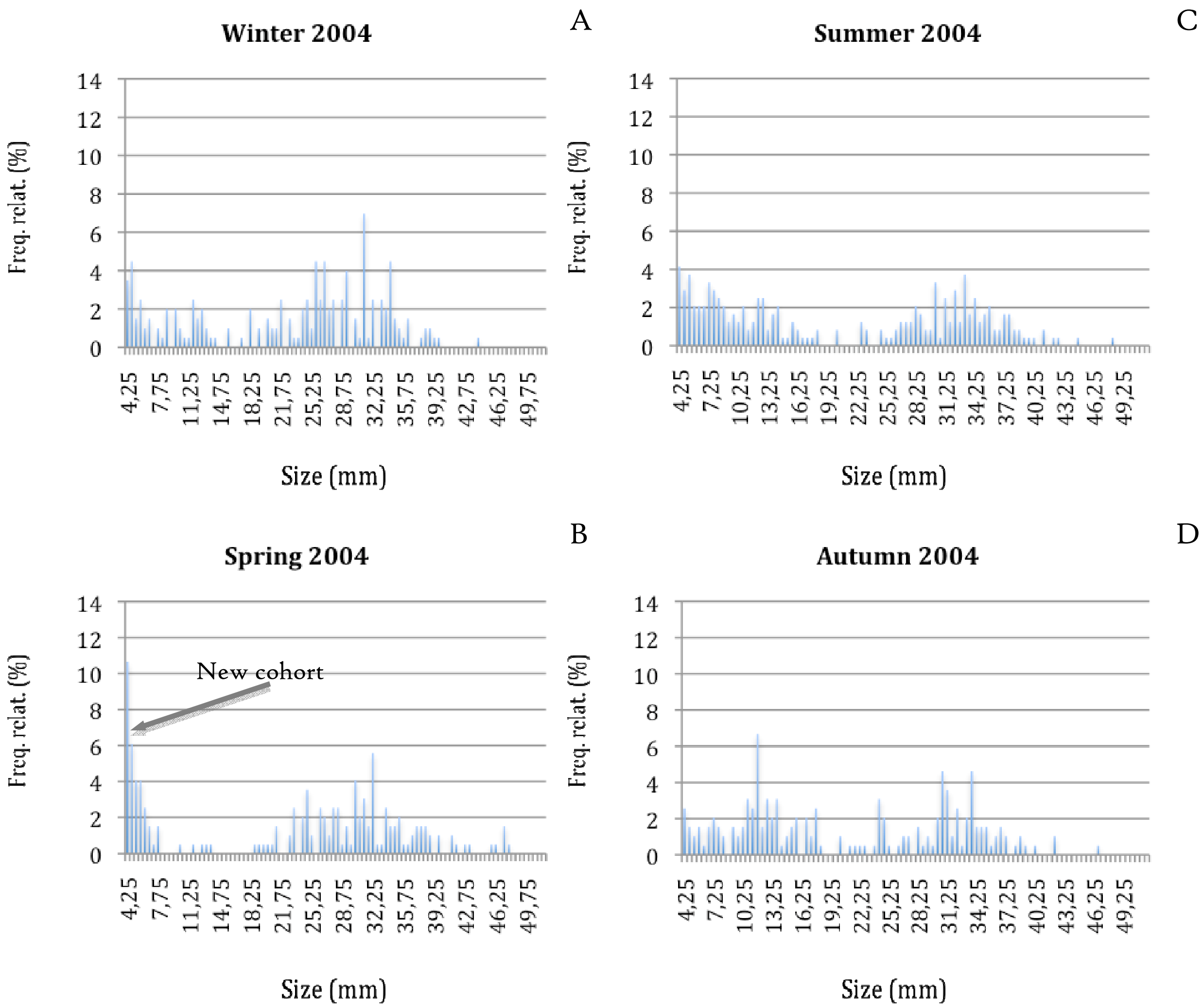


Fig. 10 - Structure of the population of *Scrobicularia plana* in 2004.

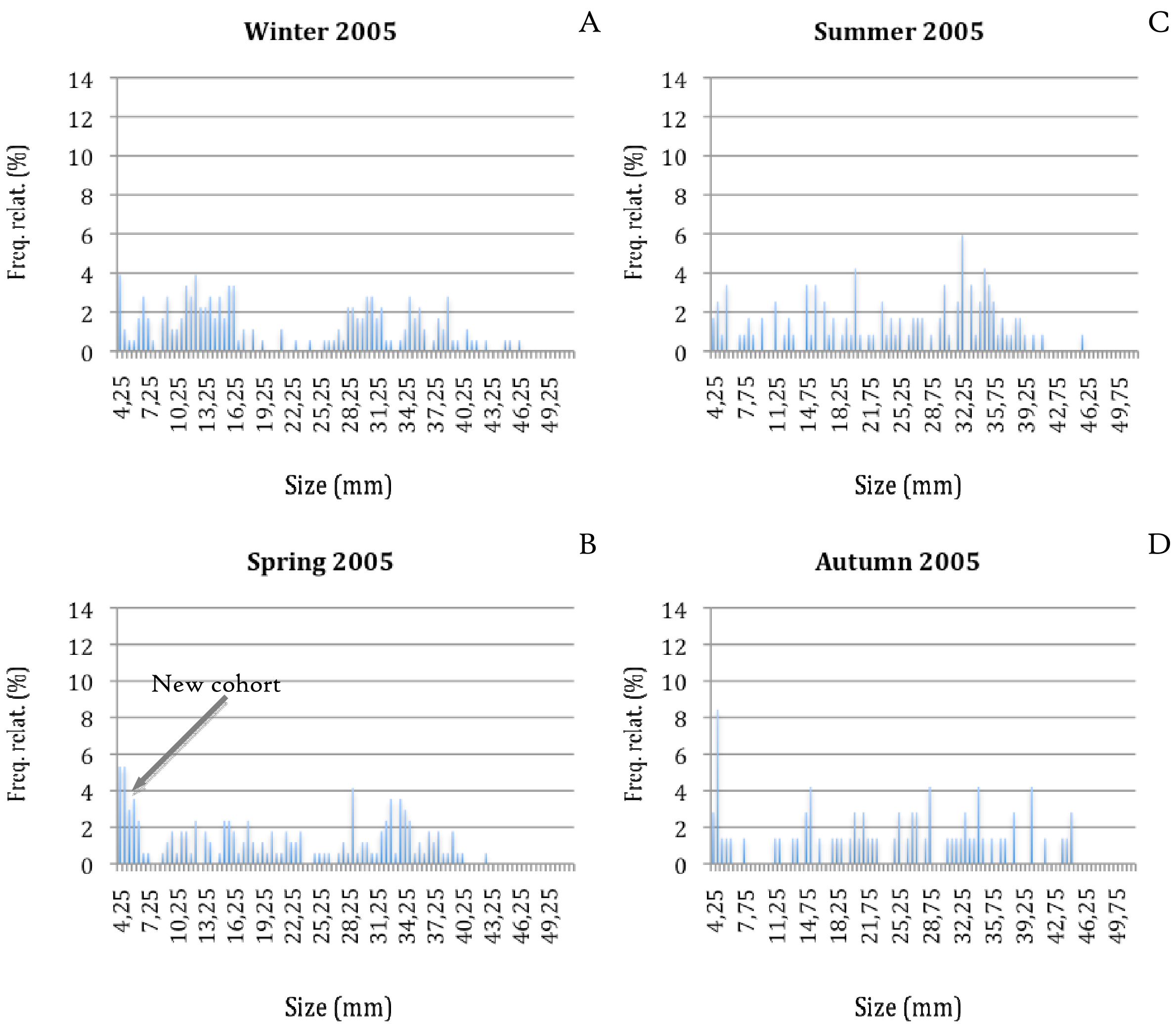


Fig. 11 - Structure of the population of *Scrobicularia plana* in 2005.

3.5. Production

The growth production and the mean population biomass of *Scrobicularia plana* in 2000 and 2001 were always higher than in 2004 and 2005. In the Table II we can see that both, flood and drought, caused a decrease in growth production and biomass, but flood had a bigger impact than drought (2000/2001: P decrease from 21.49 to 16.17 $g.m^{-2}.year^{-1}$, against 2004/2005: P decrease from 14.04 to 12.34 $g.m^{-2}.year^{-1}$).

Table II - Annual production (P: $g.m^{-2}.year^{-1}$), mean biomass ($\overline{B}$: g(AFDW).m^{-2}), and P/$\overline{B}$ (P/$\overline{B}$: $year^{-1}$) ratio estimates for *Scrobicularia plana* in Mondego estuary.

		P ($g.m^{-2}.year^{-1}$)	B ($g.m^{-2}$)	P/B
Flood	**2000**	21,49	23,30	0,91
	2001	16,17	19,69	0,79
Drought	**2004**	14,04	17,44	1,01
	2005	12,34	14,14	1,05

3.6. Stock loss

The variation of stock of *Scrobicularia plana* in Mondego estuary during the flood of 2000/2001 and the drought of 2004/2005 is shown in the Table III. We can see that the stock lost during the severe drought is higher than in the heavy flood (24.81% in the drought against 21.09% in the flood), nevertheless both caused a huge impact in the population biomass. In spite of the inexistence of data about the recovery of the population after the drought, thus not being possible to compare the two different recoveries, we can see that the biomass increased 11.01% after the flood until the end of 2001, revealing that the population was able to considerably recover from this extreme climate event.

Table III - Stock variation in *Scrobicularia plana* in the Mondego estuary ($\overline{B}$: g(AFDW).m^{-2}).

		biomass	differences	% biomass	
2000/2001	**pre-flood**	24,64			
	flood	18,52	6,11	24,81	**loss**
	post-flood	20,56	2,04	11,01	**recovery**
2004/2005	**pre-drought**	18,24			
	drought	14,39	3,85	21,09	**loss**

4. Discussion

During the last decades global climate has suffered many changes, showing a global warming tendency and increased frequency and intensity of extreme weather events. Climate in Portugal is not an exception and several extreme weather events were observed in the last years. During the winter of 2000/2001 heavy rainfall caused the largest flood of the century, and the severe drought occurred in 2004 and 2005 as a consequence of low precipitation. These events had severe impacts in the macroinvertebrate benthonic communities (Dolbeth et al., 2007; Cardoso et al., 2008b). Moreover, this ecosystem has been on a recovery process, from a very euthrophied condition, since 1998 (Verdelhos et al., 2005; Dolbeth et al. 2007; Cardoso et al., 2005, 2007, 2008a; Lillebø, 2005). Each one of these stressors (e.g. euthrofication, extreme weather events) does not affect the system individually, but through combined and synergistic processes, decreasing the resistance and resilience of macrofauna (Adams et al., 2005; Cardoso et al., 2005, 2008b; Dolbeth et al., 2007).

Scrobicularia plana is a deposit-feeding species of bivalve and is of extreme importance in Mondego macrobenthic communities in terms of abundance, biomass and production (Verdelhos et al., 2005; Dolbeth et al., 2007; Cardoso et al, 2008b). Its response to any changes in the environment will affect the whole trophic web, and consequently the fishermen population that exploits the mudflats directly with profound economic impacts (Cardoso et al, 2008b).

The variation of water salinity in the Mondego estuary during 2000/2001 follows precipitation for the same period, showing a typical seasonal pattern. With the increase of the rainfall, water salinity in the estuary consequently decreases to drastic values (< 5 $g.l^{-1}$), reaching a value close to 0 $g.l^{-1}$ in January of 2001 corresponding to the higher values of precipitation. Extremely low salinity values have huge negative impacts on the resident species, particularly on *S. plana*, increasing mortality and affecting recruitment patterns and population dynamics and production (Hughes, 1970; Essink et al., 1991; Sola 1997; Verdelhos et al., 2005). Although, these low salinity was not maintained for long periods, revealing an increase after February of 2001, and leaving a chance to macrofauna recover. As observed in Fig. 5 A the biomass mean of *S. plana* stop declining and remained quite constant since March 2001 until the end of the same year. This could be a positive response to salinity increment.

The heavy rainfall registered in the winter 2000/2001, causing the huge flood, affected the abundance, biomass and production of *S. plana* (Cardoso et al., 2008b*)*. The most significant fall in biomass observed started in the end of summer of 2000 ending in January 2001. But this was not the most affected parameter in this population. Juvenile recruitments were severely affected by the flood. In fact, in 2001 any recruitment of this bivalve species was not registered. Intense rainfall flushed away a significant part of the population in direction to the sea, mainly affecting juveniles since they are not so buried in the sediment and has a much lower biomass. Along the year of 2001 the abundance of juveniles was extremely low and just started increasing after October of the same year. Another cause of extreme flooding was the high turbidity of the water, resulting in clogging up the feeding structures of this bivalve species (suspension feeders), which affects its survival and performance (Norkko et al. 2002; Cardoso et al., 2008b). The biomass of mature adults followed the trend of the biomass mean of the whole population, having just a significant decline in the winter of 2000/2001, and getting quite stable after March 2001 remaining like that until the end of the year. The behaviour of juvenile density along 2000 ad 2001 is identical to the one of the total population, indicating that the low values of salinity affected every individual's classes.

During 2004 and 2005, years characterized by the severe drought, unusual constant high water salinity were registered, explained by the extremely low precipitation during this period and specially in the winter of 2004/2005. This fact reduces the river hydrodynamics increasing the water residence time, keeping salinity above regular values, also a result of the intake of the seawater in the estuary. That made possible the salinity values to reach the 35 $g.l^{-1}$ in the summer of 2005, which corresponds to a normal salinity in the ocean.

The population of *S. plana* suffered a constant decline in the mean population biomass, through a cycling oscillatory behaviour, right after June 2004. Again, in these years the biomass of mature adults followed that tendency. In this drought scenario the whole structure of population, is mainly affected by the extremely high values of salinity (Casagranda and Boudouresque, 2005), being the most important parameter to define the population dynamics. Although, the high water temperature is also important (Casagranda and Boudouresque, 2005). Juvenile recruitments were registered in 2004 and in 2005 both in the end of winter, but they were significantly reduced when compared to the recruitment in the beginning of 2000, right before the flooding. Juvenile abundance evolution is similar to that of total population, giving us the idea that all individuals are equally affected.

Analyzing the population structure along 2000 and 2001 is clear the negative influence of the flood. The new cohort shown in the spring of 2000 is no longer seen in the next seasons. The high mortality rate and the low recruitment success led to a poorly structured population over time. During the period of 2004 and 2005, the population seemed very structured in the beginning of 2004, being easy to distinguish the new cohort in the spring. But then, just like in the flood, that structure started to vanish after autumn of 2004. In the spring of 2005 it is barely perceived any cohort and the tendency is maintained until final of the year. The new cohort in the spring of 2005 is much shorter than any other registered.

Comparing the two extreme climate events in terms of consequences to *Scrobicularia plana* population dynamics, we conclude that the flood cause a strong impact in the recruitment success and the extremely low values of water salinity affect the density and biomass, moreover during the drought, the impact is more uniform in the whole population affecting in the same way every individuals, because the main stressor is the salinity, having a bigger impact in the population mean biomass.

Growth production is severely reduced during these extreme climate events. That is a direct result of the decrement of the mean population biomass. The percentage of stock loss of this species is almost 25% in the flood and about 21% during the drought, which is an extremely high loss and provokes a consequent lowering of the resistance and resilience of this population to further stress scenarios.

5. Conclusions

This study showed that extreme flooding and drought events drastically declined the population of *Scrobicularia plana* in the Mondego estuary. It caused great impacts to the estuary macrofauna community, since this species has a huge ecological importance in this ecosystem, contributing to its degradation and lowering overall system stability. Local fishermen were also very affected by these events concerning the commercial importance of this bivalve species (Cardoso et al., 2008b). This has implications for biodiversity conservation of Mondego estuary and for the people who depend on it.

Extreme climate events will become more frequent in the next years, thus understanding its negative ecological and socio-economical consequences, has become essential to avoid additional anthropogenic stressors and predicting responses to environmental change (Cardoso et al., 2008).

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