Benthic foraminifera as indicators of habitat change in anthropogenically impacted coastal wetlands of the Ebro Delta (NE Iberian Peninsula)

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A B S T R A C T

Present-day habitats of the Ebro Delta, NE Iberian Peninsula, have been ecologically altered as a consequence of intensive human impacts in the last two centuries (especially rice farming). Benthic foraminiferal palaeoassemblages and sediment characteristics of five short cores were used to reconstruct past wetland habitats, through application of multivariate DCA and CONISS techniques, and dissimilarity coefficients (SCD). The timing of environmental changes was compared to known natural and anthropogenic events in order to identify their possible relationships. In deltaic wetlands under altered hydrological conditions, we found a decrease in species diversity and calcareous-dominated assemblages, and a significant positive correlation between microfaunal changes and organic matter content. Modern analogues supported palaeoenvironmental interpretation of the recent evolution of the Delta wetlands. This research provides the first recent reconstruction of change in the Ebro Delta wetlands, and also illustrates the importance of benthic foraminifera for biomonitoring present and future conditions in Mediterranean deltas.

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1. Introduction

Coastal ecosystems (e.g. deltas, wetlands, estuaries) are both naturally and artificially subject to many and varied environmental changes (Elliott and Quintino, 2007). Due to their location at the land–sea interface, these transitional waters have a strong intrinsic dynamism and pronounced environmental gradients (e.g. salinity, nutrients, sediment types, oxygen levels) (LePage, 2011). Some of these natural gradients, however, are often drastically modified by human activities, particularly in deltas, which are often densely populated and heavily farmed (Syvitski et al., 2009). Among human impacts in Mediterranean coastal wetlands, changes in land and water uses and demand for agricultural purposes have caused the largest serious modifications of their natural ecological functioning. These changes have altered wetland habitat structure across a variety of spatial and temporal scales, mainly by artificial freshwater inputs and eutrophication (Margalef and Mir, 1973; Pérez-Ruzafa et al., 1991; Marco-Barba et al., 2013; Prado et al., 2014). Furthermore, intensive agricultural and human settlements have eliminated most of the original distribution of coastal wetland habitats (Benito et al., 2014; Halpern et al., 2008).

Given the accepted ecological and economic importance of coastal wetlands (Costanza et al., 1997), well-informed and climate-resilient management is essential to maintain the proper functioning of the remaining natural ecosystems, while allowing exploitation for agriculture, tourism and/or industry. Unfortunately, due to the lack of long-term monitoring data, palaeoecological information is the only archive to document past environmental changes (Smol, 2002; Willis and Birks, 2006).

Existing literature shows that benthic foraminifera (unicellular protists) are widely used to study both present and past environmental conditions in many coastal ecosystems around the world (Horton et al., 2007; Pruitt et al., 2010; Cheng et al., 2012; Takata et al., 2014). Their fossil remains are commonly used in climate reconstruction but they also allow tracking environmental changes due to human impacts over last hundreds years (Cearreta et al., 2002; Debenay and Fernandez, 2009). Numerous ecological studies have employed different multivariate statistical techniques for interpreting modern foraminifera–environment relationships, and then for applying those into dated sediment cores (Vance et al., 2006; Kemp et al., 2012; Narayan et al., 2015). Benthic foraminifera living in coastal marshes respond to a broad range of biotic and abiotic factors that result in complex interactions in space and time (Debenay and Guillou, 2002). Moreover, palaeoenvironmental reconstructions should demonstrate the similarity

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between modern and buried microfaunas to provide accurate inferences (Guilbault et al., 1996). In this context, combined approaches are required, using modern foraminiferal analyses coupled with palaeoecological information and independent sediment proxies (e.g. organic matter).

The proportion of transitional waters that can be considered to have “high ecological status” (i.e. reference conditions) is very limited but important for management purposes. Successful management requires good understanding of ecosystem structure and functioning under pre-impacted conditions in order to set realistic restoration goals. The Water Framework Directive (WFD) requires the degree of deviation from these reference conditions to be documented using hydromorphological, physicochemical, and biological quality elements (European Communities, 2003). As other authors have highlighted, reference conditions should preferably be assessed in situ, rather than comparing the area in question with similar systems elsewhere (if any) that have not been altered by human activities (Blanchet et al., 2008; Alve et al., 2009). This is particularly relevant in the case of transitional ecosystems, due to the great heterogeneity of ecological conditions within them (Alve, 1995; Bald et al., 2005). Palaeoecological approaches can allow objective assessment of local “reference conditions” for any type of water body (river, lake, coastal waters) (Andersen et al., 2004).

Down-core benthic foraminiferal assemblages have recently been used to determine whether human activities have changed “baseline” conditions in marginal marine environments (Tsujimoto et al., 2008; Martínez-Colón et al., 2009; Alve et al., 2009; Bouchet et al., 2012; Dolven et al., 2013). Benthic foraminifera are not required by the WFD (Annex V) as biological quality elements for monitoring transitional waters and have rarely been used as ecological indicators of anthropogenic disturbances in Mediterranean coastal environments (Carboni et al., 2009), with the exception of the Venice lagoon (Donnici et al., 1997; Serandrei-Barbero et al., 1999, 2011; Albani et al., 2007; Coccioni et al., 2009). Another group of unicellular benthic eukaryotes, the diatoms, are widely used in biomonitoring (indeed, their use is required by the WFD for assessing some water bodies, e.g. rivers, though not transitional waters) and proved valuable as ecological indicators in an earlier study of the Ebro Delta (Benito et al., 2015). However, the lack of well-preserved diatom remains in some Delta sediments led us to focus instead on foraminifers in the present study.

The present paper represents the first study using benthic foraminiferal palaeoecology within a Mediterranean delta. The main objective was to examine the effects that intensive human settlement has had on the habitats of the Ebro Delta during the last two centuries. We aimed to document the effects of rice field expansion and hydrological changes by studying the buried foraminiferal assemblages preserved in five short sediment cores. An additional aim was to compare the recent evolution of two contrasted wetland types within the Delta represented by four sites under altered hydrological conditions, and one site under a natural brackish hydrological regime.

2. Material and methods

2.1. Study area

The Ebro Delta is one of the largest coastal wetlands in the Western Mediterranean, extending over an area of about 330 km², and is situated in the NE Iberian Peninsula (Fig. 1). The Delta is irrigated by the Ebro River, which is the largest river in Spain in terms of mean annual flow (c. 400 m³ s⁻¹). The drainage area of the Ebro River is 85,550 km², representing 15% of the total area of Spain (Maldonado and Murray, 1975). Nowadays a large amount of the water that the river would have carried under natural conditions is extracted for irrigation and other purposes. Consequently, the amount of water and sediment reaching the Delta has been drastically reduced, particularly between 1940 and 1970, when nearly 200 dams were built (Ibáñez et al., 1996).

From an ecological point of view, the Ebro Delta is important due to its high diversity of Mediterranean coastal wetlands concentrated in a small area (Ibáñez et al., 2000). This is in part due to the micro-tidal nature of the Delta (with an astronomical range of only 20–30 cm), which allows high spatial heterogeneity of wetland habitats structured in small patches (Ibáñez et al., 2000). The Ebro Delta is also economically important, with two thirds of the area devoted to rice crop, but also

![Fig. 1. Location of the Ebro Delta. The positions of the cores (white triangles) are shown in both historical (1927, left side) and modern (2015, right side) aerial photographs; a) Olles; b) Ganxal; c) Clot, Alfacs and Tancada. Scale bar represents 1 km. Historical photographs were obtained from the Ebro Water Authority (www.chebro.es).](image-url)
with other activities such as tourism, aquaculture or hunting that contribute to the total annual economic value of about €120 million (Fatoric and Chelleri, 2012).

During the last two centuries, most of the deltaic plain has been reclaimed for rice cultivation. Agriculture was poorly developed in the Delta until the 19th century, when intense landscape transformation began (in the 1860s) with the construction of the south irrigation channel derived from the Ebro River, and rose drastically from 1912, when the construction of the north irrigation channel was completed (Rovira and Ibáñez, 2007). Even so, at the beginning of the 20th century, natural habitats still covered 80% of the total deltaic area (Mañosa et al., 2001). Outside the area of rice cultivation, human activities were based on subsistence economy (farming, salt production, fishing and hunting), which did not cause widespread transformation of the area. The period between 1910 and 1960 saw rapid development of rice farming in the Delta, which resulted in a drastic loss of fresh, brackish and salt marshes, and lagoons as they were converted to paddy fields (Cardoch et al., 2002). Transformation for rice cultivation started from the inner part of the Delta and areas adjacent to river levees (which were naturally more elevated and had less saline soils) and advanced progressively seaward. Altogether, the surface area occupied by natural habitats reduced from 80% to 33% between 1910 and 1960 (Mañosa et al., 2001). Transformation continued during the next two decades (1960–1980), stopping only in the 1980s, when the Ebro Delta Natural Park was created (1983). The area still covered by marshes and coastal lagoons amounts to just 25% of the deltaic plain, but this contains good examples of a diversity of Mediterranean coastal wetlands, including salt and brackish marshes, coastal lagoons, sand dunes, freshwater marshes, ponds and bays. Most of these habitats are protected by European Directives (e.g. the Habitat Directive and Bird Directive) and regional environmental laws (for the Ebro Delta Natural Park).

Rice field cultivation necessitates large-scale control of water inputs and outputs and so an extensive system of irrigation and drainage canals has been constructed in the Delta. From the 1860s to the late 1980s, runoff from the rice paddies was drained directly into the remaining lagoons during the rice growing season (i.e. from April to September), and then from these systems into the sea (in the Alfacs and Fangar bays: Fig. 1). The main consequence has been the alteration of the natural hydrological cycles of the coastal lagoons and surrounding marshes (Prado et al., 2012, 2014; Rodríguez-Clement et al., 2013) and the bays (Llebot et al., 2011). These freshwater inputs also carry nutrients and pesticides, altering further the ecology of the habitats. Moreover, the construction of infrastructures such as canals, dikes and roads has contributed to the isolation of the remaining natural habitats from the Ebro River and Mediterranean Sea (Ibáñez et al., 1997), with the exception of the Garxal wetland located at the river mouth area and the marshes located along the outermost edges of the Delta.

2.2. Core sampling and chronology

Five short sediment cores, two placed in the northern hemidelta (Olles and Garxal, Fig. 1) and three in the southern one (Tancada, Alfacs and Clot, Fig. 1), were retrieved from sites well within marshes in April 2014. The locations were chosen to cover a range of different environments affected historically by natural and human factors (Table 1 and Appendix B). Each core was collected to a depth of 65–106 cm (depending on marsh soil thickness) using a hand-operated Beeker-type corer of 5.7-cm diameter, which allows recovery of undisturbed sediments.

The five cores collected in 2014 were taken at exactly the same locations as some short cores (50 cm length) collected in 2009, which were dated with $^{210}$Pb (Table 1). $^{210}$Pb is a natural radionuclide with a half-life of 22.3 years, and is continuously introduced into the aquatic systems by atmospheric deposition, after radioactive decay of $^{222}$Rn. Core samples for determining $^{210}$Pb activities were sliced into 4 cm sections. Each sample was first homogenized in a mortar and then dried at 60 °C. Dried samples were placed in 65 cm$^3$ Petri dishes, and then counted for 20 to 90 h in the CRIL-RAD laboratory (France). Determination of $^{210}$Pb activities was carried out using a gamma hyperpure germanium “N” type detector (EGG/ORTEC, Type GMX) coupled to a multichannel analyser (type NUCLEUS) and calibrated by a pitchblende gamma multiray source.

The chronology was tentatively inferred on average sediment accumulation rate (cm/year) using the exponential-type decline of $^{210}$Pb$^{\text{excess}}$ with depth (Fig. S1 and Table S1). The model applied (Constant Initial Concentration, CIC) assumes that the initial $^{210}$Pb$^{\text{excess}}$ concentration into the accumulated sediment is the same regardless of changes in the sediment accumulation rate in depth (Appleby, 2001). Note that the $^{210}$Pb methods do not provide absolute ages but rather gives sedimentation rates that can be indirectly used to determine how much time has elapsed between samples at different depths (Augustinus et al., 2006). We assume that the estimated chronology from these dated cores is also applicable to the five cores studied in the present study.

2.3. Foraminiferal analysis

Cores were sliced at 5-cm intervals in the field, and part of each, corresponding to a target weight of about 120 g of wet sediment was retained for foraminiferal analysis. The remaining material from each segment was used to estimate the organic matter content, as loss on ignition (LOI at 450 °C for 4 h) (Dean, 1974). The foraminiferal samples were wet washed through 1 mm and 0.063 mm sieves (to remove first large organic fragments, then silt and clay), and dried at 50 °C for 12 h. Foraminifera were concentrated by flotation in trichloroethylene (Alve and Murray, 1999). For each sample, foraminiferal tests were picked on representative splits containing at least 300 tests under a Leica M165C stereomicroscope, using reflected light. Otherwise, all the tests present in the sample were picked. Only those samples with at least 100 tests were used for numerical analyses (Fatela and Taborda,

Table 1

<table>
<thead>
<tr>
<th>Site</th>
<th>Elevation (cm)</th>
<th>$^{210}$Pb sedimentation rate (cm/yr)</th>
<th>Habitat</th>
<th>Historical human impacts</th>
<th>Habitat evolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Olles</td>
<td>6.2</td>
<td>0.24</td>
<td>Phragmites marsh</td>
<td>Freshwater inputs and high nutrient levels coming from rice field drainage channels and urban waste water</td>
<td>From coastal lagoon/inner bay to brackish marsh</td>
</tr>
<tr>
<td>Tancada</td>
<td>13.6</td>
<td>0.17</td>
<td>Salicornia marsh</td>
<td>Drainage waters coming from rice fields caused a strong decrease of salinity and high nutrient loads</td>
<td>From coastal lagoon/inner bay to salt marsh</td>
</tr>
<tr>
<td>Alfacs</td>
<td>1.1</td>
<td>0.37</td>
<td>Salicornia marsh</td>
<td>Freshwater inputs from rice field drainage waters provoked a decrease in salinity and high nutrient loads</td>
<td>From inner bay to salt marsh (backshore)</td>
</tr>
<tr>
<td>Clot</td>
<td>1.3</td>
<td>0.70</td>
<td>Phragmites marsh</td>
<td>Persistent freshwater inputs from the Ebro river and irrigation channels lead to low salinity</td>
<td>From coastal lagoon/inner bay to brackish marsh</td>
</tr>
<tr>
<td>Garxal</td>
<td>9.9</td>
<td>0.21</td>
<td>Phragmites marsh</td>
<td>Natural brackish conditions due to its direct connection to the Ebro river since the last recent mouth change (60 years ago)</td>
<td>From coastal lagoon/inner bay to coastal lagoon</td>
</tr>
</tbody>
</table>
2002). Altogether, 82 samples and around 25,400 foraminifera were examined for the five cores. Taxonomic identifications were based on foraminiferal works from the W Mediterranean, including Murray (1971), Colom (1974), Cimerman and Langer (1991) and Milker and Schmiedl (2012).

The palaeoenvironmental interpretation of the foraminiferal record was based on the modern (living and dead) distributions of species in the Ebro Delta. Benito et al. (under review) recognized four habitat types based on species composition. These habitats cover a wide range of modern analogues from both the deltaic plain and the adjacent marine area and comprise: 1) offshore, 2) nearshore and outer bays, 3) coastal lagoons and inner bays, and 4) salt and brackish marshes. In addition, foraminiferal species regularly found in living assemblages (i.e. those foraminifera that got stained after treated with rose Bengal, see Walton (1952) for method details) of the modern samples of Ebro Delta habitats were considered as autochthonous (living and reproducing within the delta plain), whereas those found only as dead tests (i.e. unstained) were considered to be allochthonous species transported from the adjacent marine area (Murray, 2006; Cearreta et al., 2013; Rodriguez-Lazaro et al., 2013, Benito et al., under review).

2.4. Data analysis

We calculated the relative abundance (RA) of foraminifer species for each core sample. Foraminiferal relative abundances were square root transformed prior to statistical analyses in order to stabilize their variances. Only those species with >2% of relative abundance in at least one sample were used in the analyses.

To analyse changes in the foraminiferal assemblages throughout the cores, depth intervals (DIs) were defined by stratigraphically constrained cluster analyses (CONISS) and the squared chord distance to the species data. Clusters were constrained by stratigraphic order, and the statistical significance of each cluster was determined using the “broken stick” method (Bennett, 1996).

A Detrended Correspondence Analysis (DCA) was used to visualize the trajectory of change of each core through unconstrained ordination space in which modern (dead) foraminiferal samples were also passively plotted (Benito et al., under review). The same multivariate ordination was used further to determine whether buried foraminiferal samples were represented by the modern Ebro Delta habitats. In order to aid interpretation of DCA ordination axes, environmental variables (water depth, salinity and sand content) from modern dataset (Benito et al., under review) were entered using the ‘envfit’ function within R’s vegan package with 999 permutations. The ‘envfit’ function provides information about the statistical relationship of the environmental vectors to the DCA axes. Thus, the length of each vector is proportional to the correlation between the ordination axes and environmental variables. Finally, for each sediment core, we calculated statistical correlations between DCA axis scores and organic matter content using Pearson r coefficient.

To check the degree of dissimilarity (or similarity) in the foraminiferal assemblages between each buried sample and the modern ones, we calculated the squared chord distance (SCD) as a dissimilarity coefficient (Overpeck et al., 1985). We chose the largest dissimilarity coefficient among all modern foraminiferal samples as a critical threshold to determine whether the buried samples had “close” modern analogues (Woodroffe, 2009). Samples with SDC < 0.271 were considered similar.

All the numerical analyses were performed using R version 3.0.1 (R Development Core Team, 2010), including the packages vegan (Oksanen et al., 2013), rioja (Juggins, 2014) and analogue (Simpson and Oksanen, 2014).

3. Results

A total of 81 benthic foraminiferal species (range 4–24 species per sample) were identified from 82 samples derived from the five cores analysed in this study (Appendix A and Table S1). Of these species, 31 had a relative abundance >2% in at least one sample and were retained for statistical analysis. The sediment cores were mainly composed of grey muddy sand (10–80% sand content) with sandier layers (>90% sand content) generally increasing downwards in the cores.

3.1. Olles

Two distinct depth intervals (DIs) were identified within the Olles core (Fig. 2 and Table 2). The basal D2 (32–70 cm depth) was characterized by the dominance of hyaline foraminifera, with Ammonia beccarii (average relative abundance [RA] 54%) and Haynesina germainica (average RA 39%) as the dominant species. The allochthonous hyaline Brizalina variabilis, Cribroelphidium selseyensis and Asterigerinata mamilia appeared in this zone as secondary species, with average RA of 1–5%. D2 was also characterized by a gradual decrease of organic matter content with depth. The following D1 (0–32 cm depth) was characterized by a shift to an agglutinated-dominated assemblage, with Hapalophysgmoideas wilberti as the most abundant form (average RA 82%). This DI1 showed a reduction of species richness and relatively high organic matter content (average 31%).

3.2. Tancada

Three distinct DI were identified within the Tancada core (Fig. 2 and Table 2). The basal DI3 (67–106 cm depth) was characterized by a mixture of hyaline (average RA 91%) and porcellaneous foraminifera (average RA 9%). A. beccarii and H. germanica were the dominant species within DI3. Overlying DI3, the second depth interval (DI2, 12–67 cm depth) showed a very similar species composition, with A. beccarii and H. germanica as the dominant species, and Cribroelphidium oceanensis and Cribroelphidium sp.1 as secondary species. This DI2 was also characterized by the presence of Quinqueloculina seminula and other miliolids, with a peak of abundance around 40–45 cm depth. The topmost DI1 (0–12 cm depth) showed an abrupt shift in the foraminiferal assemblages: the calcareous species disappeared, and the foraminiferal assemblages were entirely dominated by the agglutinated Jadammina macrescens and Trochammina inflata (Fig. 2). Species richness was low (average 6) and organic matter content was high (average 49%, range 37–58%).

3.3. Alfacs

Three distinct DI were distinguished within the Alfacs core (Fig. 2 and Table 2). The basal DI3 (37–65 cm depth) was characterized by the presence of the hyaline marine species Buccella granulata, Aubignyna cf. perlicida, A. mamilia and Tretomphalus cf. concinsus. The overlying DI2 (12–37 cm depth) was marked by an increase of porcellaneous foraminifera (average RA 49%). There was also an increase of other marine species such as Haynesina depressula and Cribroelphidium sp.1, and sand content in relation with underlying DI3. The topmost DI1 (0–12 cm depth) was dominated by agglutinated species J. macrescens and T. inflata (average RA 54%), with a minor contribution of A. beccarii and miliolids. DI1 also showed the highest organic matter content of the core (Fig. 2). The species richness was slightly lower than in DI2 and DI3.

3.4. Clot

The Clot core was divided into two distinct DIs (Fig. 2 and Table 2). The basal DI2 (42–90 cm depth) had high relative abundances of A. beccarii (average 74%). This interval showed also an average of 13 allochthonous species, in particular Q. seminula, Cribroelphidium sp.1 and miliolids appeared at 60 cm depth. The sand content was very high throughout this DI2 (average 92.7%). The overlying DI1 (0–42 cm depth) was characterized by a mixture of hyaline and agglutinated
Fig. 2. Stratigraphic diagrams of the five studied cores in the Ebro Delta: sand content (%), organic matter content (%), main foraminiferal species (>2% RA at least in one sample), DCA axis 1, CONISS cluster analysis, and core trajectories projected onto the DCA along with modern samples. Dashed lines in DCA plots encompass modern habitat samples of each habitat type identified in the Ebro Delta according to Benito et al. (under review): A) offshore; B) nearshore and outer bays, C) coastal lagoons and inner bays, and D) salt and brackish marshes. Environmental vectors are fitted on top of each DCA plot. Notice that the DCA axis 1 scale differs among each diagram.
foraminifera, with *A. beccarii* (average RA 63%), *H. germanica* (18%) and *J. macrescens* (11%). This DI2 showed a gradual decrease of the allochthonous component and an increase of the organic matter content towards the top.

### 3.5. Garxal

Two distinct DI2s were recognized in the Garxal core (Fig. 2 and Table 2). The basal DI2 (32–70 cm depth) was characterized by a mixture of hyaline (average 89%) and porcellaneous (average 11%) foraminifera. The mean allochthonous content through this DI2 interval was 23%, with the appearance of different marine foraminifera, such as *H. depressula, B. granulata* and *Cibicides lobulatus*. The top DI1 (0–32 cm depth) showed an increase of hyaline foraminifera (average 99%), with *A. beccarii, H. germanica*, and several *Cribroelphidium* species (e.g. *C. excavatum, C. oceanensis* and *C. poeyanum*) as dominant species. The proportion of allochthonous foraminifera was slightly higher than in DI2, where the average was 26%.

### 3.6. Core trajectories and analogue matching

Core trajectories, illustrated in Fig. 2, showed that Olles, Tancada and Clot indicated a clear habitat shift from coastal lagoons and inner bays to salt and brackish marshes. Alfaacs showed a trajectory from nearshore habitats to salt and brackish marshes (Fig. 2). On the other hand, the core trajectory of Garxal showed that this site did not experience significant habitat change, since its whole trajectory lay within the coastal lagoon and inner bay habitat (Fig. 2).

The buried foraminiferal samples, when plotted passively onto DCA ordination with the modern samples, also showed that Olles, Clot and Alfaacs cores were arranged along DCA axis 1, but Tancada and Garxal cores mainly along axis 2 (Fig. 2). Salinity was significantly correlated with both ordination axes ($r^2 = 0.57$, $p < 0.001$). There was also a significant relationship between the first two DCA axes and water depth ($r^2 = 0.31$, $p < 0.001$) and sand content ($r^2 = 0.10$, $p < 0.001$). Organic matter content was significantly and positively correlated with DCA axis 1 scores (Pearson $r > 0.80$, $p < 0.01$), except for the Garxal core.

Most of the core samples from Olles, Clot, Tancada and Garxal showed low dissimilarity distances from the modern data set (SCD < 0.271), implying that they have “close” modern analogues (Fig. 3). High dissimilarity distances (SCD > 0.39) were observed in two samples of the Alfacs core, one in DI3 and the other in DI1, where relatively high average RAs (i.e. 10–30%) of marine species were found. Very similar results were found in one sample of Garxal core (DI2) (Fig. 3).

### 4. Discussion

Detailed knowledge of modern foraminiferal distributions and ecology in the Ebro Delta (Benito et al., under review) was used to reconstruct environmental changes in the five studied cores. As in similar microtidal systems elsewhere (Alve and Murray, 1999; Serandrei-Barbero et al., 2011), the dead foraminiferal assemblages of the Ebro Delta have proved to be a good reflection of the living ones, with a mean similarity of 72.9% based on Rogers index (Benito et al., under review). Although calcareous and agglutinated foraminifera can be prone to dissolution once buried in the sediments (Boltovskoy and Wright, 1976; Murray and Alve, 1999), in the present study foraminiferal tests were abundant in almost all samples and very well preserved. Therefore, because of the positive performance of these two factors (i.e. similarity between living and dead assemblages, and good test preservation) modern and buried assemblages can be properly compared in order to interpret the palaeoenvironmental changes recorded in the Ebro Delta cores.

The core assemblages show that present-day environmental conditions in the Ebro Delta wetlands differ greatly from those at the end of

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**Table 2**

Summary of estimated periods and foraminiferal assemblages from the Ebro Delta studied cores. The single value represents the mean and the range is represented between parentheses.

<table>
<thead>
<tr>
<th>OLLES</th>
<th>TANCADA</th>
<th>ALFACS</th>
<th>Clot</th>
<th>Garxal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth core (cm)</td>
<td>70</td>
<td>106</td>
<td>65</td>
<td>90</td>
</tr>
<tr>
<td>Elevational range (cm)</td>
<td>1.2 to -23.8</td>
<td>8.6 to -1.4</td>
<td>-3.9 to -13.9</td>
<td>-3.7 to -43.7</td>
</tr>
<tr>
<td>Species</td>
<td>4 (4–5)</td>
<td>6 (6–6)</td>
<td>13 (7–18)</td>
<td>11 (7–15)</td>
</tr>
<tr>
<td>Estimated period</td>
<td>1930s–present</td>
<td>1970s–present</td>
<td>1980s–present</td>
<td>1980s–present</td>
</tr>
<tr>
<td>Allochthonous %</td>
<td>0.6 (0–0)</td>
<td>0.8 (0–1)</td>
<td>16.8 (3–30)</td>
<td>5.1 (0–10)</td>
</tr>
<tr>
<td>Agglutinated %</td>
<td>99.5 (99–100)</td>
<td>94.5 (94–95)</td>
<td>72.4 (48–96)</td>
<td>12.1 (0–46)</td>
</tr>
<tr>
<td>Porcellaneous %</td>
<td>0</td>
<td>0.3 (0–1)</td>
<td>6.52 (3–10)</td>
<td>0.3 (0–2)</td>
</tr>
<tr>
<td>Hyaline %</td>
<td>0.5 (0–1)</td>
<td>5.2 (5–6)</td>
<td>21.3 (1–41)</td>
<td>87.6 (54–100)</td>
</tr>
<tr>
<td>Mean allochthonous content</td>
<td>34.1 (18%)</td>
<td>11%</td>
<td>26%</td>
<td>26%</td>
</tr>
</tbody>
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Foraminiferal species diversity in the Ebro Delta (Benito et al., under review) and the significance of the foraminiferal assemblages in modern environments (Boltovskoy and Wright, 1976; D'Hondt et al., 2006).
the 1800s and in the early 1900s. The assemblages at the base of the Olles core (DI2, i.e. before the 1900s) were characterized by relatively few allochthonous components and a hyaline dominated assemblage, suggesting shallow subtidal lagoonal conditions (Murray, 2006). The habitat shift recorded in DI1, when agglutinated H. wilberti became dominant, correlates well with the wetland transformation for rice cultivation that began in the northern hemidelta in 1912, with the construction of the north irrigation channel derived from the Ebro River. Olles wetland was then largely isolated from the Mediterranean Sea (Fangar Bay, see Fig. 1), and began to receive enhanced inputs of drainage and sewage waters. A comparable assemblage occurs nowadays in the Phragmites marshes of the Ebro Delta (Benito et al., under review), which occupy the littoral zones around fresh-brackish coastal lagoons. These marshes are rich in nutrients and organic matter and are fresher than they were originally, due to freshwater inputs coming from rice field drainage. Debenay and Guillou (2002) also indicate the preference of H. wilberti for organic-rich sediments in Mediterranean coastal wetlands.

The different locations of the Alfacs and Tancada cores may explain the differences in habitat conditions recorded before the 1970s–1980s: DI3 and DI2 of Alfacs are interpreted as inner bay with high marine influence due to its near connection with the bay through a backshore marsh, whereas DI3 and DI2 of Tancada are interpreted as coastal lagoon/inner bay environment with much less hydrologic connectivity with the sea (i.e. further away from the bay, see Fig. 1). This interpretation is supported by the dominance of allochthonous foraminifera in DI3 and DI2 of Alfacs, and autochthonous foraminifera in both DI3 and DI2 of Tancada (Table 2). A higher marine influence in Alfacs is further supported by the very high dissimilarity distances in DI3 compared to those in DI3 of the Tancada core. However, although originally rather different, the Tancada and Alfacs biotopes evolved towards a similar end-point (i.e. Salicornia marsh). This habitat transition was accompanied by an abrupt microfaunal change, revealed by DCA axis 1 (Fig. 2), and by the clear dominance of agglutinated species in both DI1 intervals (Table 2). These results could be related to agricultural runoff that these two areas began to receive recently (1970s–1980s) due to water management practises: input of freshwater from rice drainage to the corner of Alfacs bay (near Alfacs site, see Fig. 1) and to the eastern side of the Tancada lagoon (near Tancada site, see Fig. 1). Environmental changes will have not only decreased salinity but also lowered pH, since rice-field runoff is generally acid (Comoretto et al., 2008). More acidic conditions are known to be favourable for agglutinated foraminifera (Alve, 1995; Scott et al., 2005; Tsujimoto et al., 2006). The dominance of agglutinated foraminifera in surface sediments at Tancada and Alfacs is comparable to that observed in the salt marshes in the Mekong Delta, where T. inflata and J. macrescens became dominant due to artificial freshwater inflows for shrimp and rice farming (Luan and Debenay, 2005).

The foraminiferal assemblages revealed that habitat changes were smaller in the Clot core than in the cores from Olles, Tancada and Alfacs, with a lesser decline in the calcareous assemblage in DI1, even though rice cultivation has developed similarly in all four areas. The reason for this may be the recent restoration of Clot lagoon that took place in 1991 (Comín et al., 1991). Since then, the freshwater inputs to Clot have mainly been direct from the river (via the irrigation canals, and therefore of better quality; Ibáñez et al., 2012), rather than from rice-field drainage. Lower pH, associated with the high organic content of the rice field runoff, decreases the availability of CaCO3 and it is known to affect calcareous foraminifera (Greiner, 1969). Interestingly, Clot is also set apart from the other three sites (Olles, Tancada and Alfacs) by the fact that it has recovered its natural macrophyte vegetation during the last 20 years, since the change to riverine water supply (Forés et al., 2002).

![Fig. 3. Barplots of square chord distance (SCD) between buried and modern (dead) foraminiferal samples for each of the five studies cores. The vertical dashed line indicates the largest dissimilarity coefficient (SCD = 0.271). Depth intervals (DIs) defined by CONISS analyses and analogue habitat types are also shown for each core.](image-url)
Although two distinct foraminiferal assemblages were found in the Garxal core, the habitat shift observed here was much less pronounced than those observed in the four other study sites, comprising only a slight decline in marine influence within the same habitat type (i.e. coastal lagoon/inner bay). This decline is very likely related to the natural change in the river mouth that took place at the beginning of 20th century. Between 1907 and 1937 exceptional river floods (up to 23,000 m$^3$ s$^{-1}$; Somozza and Rodríguez-Santalla, 2014) opened several crevasses in the northern bank three kilometres upstream from the former active mouth, offering a shorter distance to the sea (see Fig. 1; Maldonado and Riba, 1971). Then, the flow through the breach created a new shallower embayment (nowadays known as Garxal lagoon) that since 1950 has gradually become isolated from the Mediterranean Sea due to formation of sandy barriers (Maldonado and Riba, 1971). The slight increase in Garxal DII of C. selseyensis, C. poeyanum and C. excavatum, which are characteristic of living assemblages in marine habitats adjacent to the Delta (Scrutton, 1969), suggests a certain marine influence in this site.

Besides the Ebro Delta, a number of other Mediterranean coastal wetlands are fresher nowadays than they originally were, mainly due to the effects of hydrologic alterations caused by rice cultivation. This is the case, for instance, in the Albufera de Valencia (Soria, 2006; Marco-Barba et al., 2013) and Mar Menor lagoon (Pérez-Ruzafa et al., 1991) in Spain, and the Rhône Delta wetlands in France (Pont et al., 2002). Not surprisingly, therefore, studies dealing with benthic foraminifera as palaeoenvironmental proxies have focused on human-induced salinity variations as the sole predictor of coastal wetland impacts (Brewster-Wingard and Ishman, 1999; Cheng et al., 2012; Sousa et al., 2014). However, we observed that not only salinity but also water depth and sand content play a significant role in explaining the variation of the buried species composition. This suggests that foraminiferal assemblages did not change only as a result of salinity modifications, but were due instead to a combination of factors that represent a change in habitat-type. In natural systems such as deltas where most environmental factors show high spatial and temporal variability, identification of the single main factor determining foraminiferal distribution is a difficult or impossible task (Murray, 2001). This is because the foraminifera living there have a wide ecological tolerance for a high number of factors (i.e. they are eurytopic species). Thus, explanations of changes observed in the foraminiferal assemblages of the Ebro Delta and similar systems should take into account not only salinity modifications but also water depth and its fluctuations (e.g. subtidal/supratidal conditions), substrate characteristics, eutrophication, hydrological isolation (impoundment), etc.

The pattern of changes in organic matter content in our cores is consistent with the idea of habitat alteration accompanying the extensive development of rice cultivation. Seasonal inputs of rice drainage water (in April–September, i.e. during the rice growing season), with high levels of organic matter and nutrients, promote the accumulation of organic-rich sediments due to low salinities (Ibáñez et al., 2010). The general upcore increase of organic matter at Olles, Tancada, Alfacs and Clot is statistically related to changes in species composition, with a clear shift from calcareous to agglutinated foraminifera. A very similar pattern (i.e. increase of agglutinated and decrease of calcareous taxa) has been recorded in cores from Mobile Bay, Gulf of Mexico (USA), and Bedford Bay, Nova Scotia (USA) as a response to high organic loading (Osterman and Smith, 2012; Scott et al., 2005). Therefore, this core gradient may be tentatively associated to an indirect measure of habitat modification.

Human-induced changes also provoked reduction of species richness towards the top of the cores, likely reflecting deteriorating of ecological status through time (Alve et al., 2009). The very low diversity assemblages of agglutinated species observed in DII (of Olles, Tancada and Alfacs, and to a lesser extent in Clot), might be related to increasing abundance of a few opportunistic species, at the expense of species more sensitive to unfavourable conditions, e.g. low oxygen, more acidic conditions (Alve, 1995; Osterman and Smith, 2012). However, many naturally stressed habitats can also possess low diversity assemblages dominated by agglutinated forms (e.g. Murray, 2006).

The long-term results obtained give insights into the ecological conditions present in the Ebro Delta before intensive rice cultivation began at the end of 1800s and early 1900s. By characterizing present-day conditions via living foraminiferal assemblages (Benito et al., under review), the degree of deviation from natural conditions can therefore be assessed. Studies in northern Europe (Bouchet et al., 2013; Schönfeld et al., 2012) have also shown the potential of benthic foraminifera for monitoring coastal ecosystems and in fact, the Ecological Quality Status of Norwegian fjords is classified as “unacceptable” or “acceptable” using benthic foraminifera (Dolven et al., 2013). Our study indicates that this approach could usefully be extended to Mediterranean coastal wetlands to better define restoration goals and support environmental policies (e.g. Water Framework Directive).

5. Conclusions

The Ebro Delta wetland habitats have undergone clear shifts since the beginning of intensive human colonization started approximately 150 years ago. Foraminiferal assemblages track both natural- (Garxal) and anthropogenic (Olles, Tancada, Alfacs and Clot) environmental changes. At the beginning of 1900s, a significant decrease occurred in both calcareous and allochthonous foraminifera, which can be related to the transformation of most of the Delta wetlands to extensive rice agriculture. A further upcore trend is a significant loss of diversity and dominance of agglutinated foraminifera, which seems to have been a response to the increased organic matter in the sediment due to inputs of agricultural runoff.

The paleoenvironmental data obtained in this study provide a historical perspective on the Ebro Delta wetlands, which are in many ways representative of other anthropogenically impacted Mediterranean coastal wetlands. Long-term studies that combine indicators of land alterations (e.g. organic matter) and downcore changes linked to foraminifera ecology, will help to provide baselines for future monitoring and restoration strategies in Mediterranean deltas. This should be especially relevant for the Ebro Delta, which is at risk due to global change consequences such as sea-level rise and sediment deficit (Ibáñez et al., 2014).

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Appendix A

Taxonomic reference list. Each species is classified as autochthonous (AU) or allochthonous (AL) according to their components (living vs dead) in the modern assemblages of the Ebro Delta samples (see Material and methods for our definition of autochthonous and allochthonous foraminifera).
Agglutinated forms
Ammobaculites balkwilli Haynes, 1973: AL
Ammobaculites sp.1: AL
Eggerella advena (Cushman) = Verneuilina advena Cushman, 1921: AL
Eggerelloides scaber (Williamson) = Bulimina scabra Williamson, 1858: AL
Haplophragmoides wilberti Anderson, 1953: AU
Haplophragmoides sp.1: AL
Jadammina macrescens (Brady) = Trochammina inflata (Montagu) var. macrescens Brady, 1870: AU
Miliammina fusca (Brady) = Quinqueloculina fusca Brady, 1870: AU
Scherocharella moniliformis (Siddall) = Reophax moniliformis Siddall, 1886: AL
Textularia bocki 1886: AL
cf. Textularia
Textularia bocki 1886: AL
Milonella subrotunda 1939: AL
Triloculina marioni 1939: AL
Triloculina dubia 1886: AL
Quinqueloculina oblonga (Montagu) = Vermiculum oblongum Montagu, 1893: AL
Quinqueloculina quadra (Montagu) = Vermiculum subrotandum Montagu, 1803: AL
Quinqueloculina seminula (Cushman) = Quinqueloculina seminula var. jugosa Cushman, 1944: AU
Quinqueloculina longirostris d’Orbigny, 1826: AL
Quinqueloculina oblonga (Montagu) = Vermiculum oblongum Montagu, 1893: AL
Quinqueloculina quadrata Nörvang 1945: AL
Quinqueloculina seminula (Linné) = Serpula seminulum Linné, 1758: AU
Quinqueloculina stelligera Schlumberger, 1893: AL
Quinqueloculina vulgaris d’Orbigny, 1826: AL
Triloculina dubia d’Orbigny, 1826: AL
Triloculina marioni Schlumberger, 1893: AL
Triloculina rotundata d’Orbigny, 1893: AL
Triloculina trigonula (Lamarck) = Mililotes trigonula Lamarck, 1804: AL
Triloculina sp.1: AL
Mililotes undetermined: AL
Hyaliine forms
Ammonia beccarii (Linné) = Nautilus beccarii Linné, 1758: AU
Asterigerinata mamilia (Williamson) = Rotalia mamilia Williamson, 1858: AL
Aulopygina cf. perlicuda (Heron-Allen and Earland) = Rotalia perlicuda Heron-Allen and Earland, 1913: AL
Bolivina pseudopunctata Heron-Allen and Earland, 1930: AL
Bolivina striatula (Cushman) = Brizalina striatula Cushman, 1922: AL
Bolivinellina pseudopunctata (Höglund) = Bolivina pseudopunctata Höglund, 1947: AL
Brizalina spathulata (Williamson) = Textularia variabilis Williamson var. spathulata Williamson, 1858: AL
Brizalina variabilis (Williamson) = Textularia variabilis Williamson, 1859: AL
Buccella granulata (di Napoli Alliata) = Eponides frigidus var. granulatus di Napoli Alliata, 1952: AL
Bulimina elegansissima (d’Orbigny) = Bulimina elegansissima d’Orbigny, 1939: AL
Bulimina elongata d’Orbigny, 1926: AL
Bulimina gibba Fornasini, 1902: AL
Bulimina marginata d’Orbigny, 1826: AL
Cassidulina laevigata d’Orbigny, 1826: AL
Cibicides lobatus (Walker and Jacob) = Nautilus lobatus Walker and Jacob, 1798: AL
Cribroelphidium excavatum (Terquem) = Polystomella excavatum Terquem, 1875: AU
Cribroelphidium magellanicum (Heron-Allen and Earland) = Elphidium magellanicum Heron-Allen and Earland, 1932: AL
Cribroelphidium oceanicus (d’Orbigny) = Polystomella oceanicus d’Orbigny, 1826: AU
Cribroelphidium selkynis (Heron-Allen and Earland) = Elphidium selkynis Heron-Allen and Earland, 1911: AU
Cribroelphidium williamsonii (Haynes) = Elphidium williamsonii Haynes, 1973: AL
Cribroelphidium sp1: AL
Elphidium cf. earland Cushman, 1936: AL
Elphidium advenum (Cushman) = Polystomella advenum Cushman, 1922: AL
Elphidium crispum (Linné) = Nautilus crispus Linné, 1758: AL
Elphidium gerthi Van Voorhuyzen, 1957: AL
Elphidium incertum (Williamson) = Polystomella umbilicatula var. incerta Williamson, 1858: AL
Elphidium margaritaceum (Cushman) = Elphidium advenum var. margaritaceum Cushman, 1930: AL
Elphidium undetermined: AL
Fissurina marginata (Montagu) = Vermiculum marginatum Montagu, 1803: AL
Fissurina lucida (Williamson) = Entosolenia marginata (Montagu) var. lucida Williamson, 1848: AL
Gavelinopsis praeferi (Heron-Allen and Earland) = Discorbina praefera Heron-Allen and Earland, 1913: AL
Gyroidea sp.1: AL
Haynesina depressula (Water and Jacob) = Nautilus depressula Walker and Jacob, 1798: AL
Haynesina germanica (Ehrenberg) = Nonionina germanica Ehrenberg, 1840: AU
Melonis pompioides (Fitchel and Moll) = Nautilus pompioides Fitchel and Moll, 1798: AL
Nonionella atlantica Cushman, 1947: AL
Nonionella opima Cushman, 1947: AL
Planorbulina mediterranea d’Orbigny, 1826: AL
Pyrgo ornato (d’Orbigny) = Bilucina ornato d’Orbigny, 1846: AL
Reussella aculeata Cushman, 1945: AL
Rimoinopsis cf. asterizans (Fitchel and Moll) = Nonion cf. asterizans Fitchel and Moll, 1798: AL
Rosalina anomala Terquem, 1875: AL
Rosalina globularis d’Orbigny, 1826: AL
Rosalina irregularis (Rhumbler) = Discorbina irregularis Rhumbler, 1906: AL
Trichohyalus aquaioy (Bermudez) = Discorbinopsis aquaioy Bermudez, 1935: AU
Tretomphalus cf. concinum (Brady) = Discorbinopsis concinum Brady, 1884: AL
Valvulineria bradyana (Fornasini) = Discorbinopsis bradyana Fornasini, 1899: AL
Unidentified forms: AL

Appendix B Supplementary data
Supplementary data associated with this article can be found in the online version, at http://dx.doi.org/10.1016/j.marpolbul.2015.11.003. These data include the Google map of the most important areas described in this article.

References