Agricultural fingerprints in saltmarsh sediments and adaptation to sea-level rise in the eastern Cantabrian coast (N. Spain)

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Abstract

A multi-proxy approach based on benthic foraminifera, sand content, short-lived radioisotope activities, heavy metal concentrations and aerial photography was developed to characterise the process of human disturbance on the intensely impacted eastern Cantabrian coast (N. Spain) over the last two centuries. Analysis of two 50 cm long sediment cores from different saltmarshes in the Santoña estuary and their comparison with previous results in nearby coastal areas defines criteria to identify records of agricultural activities in salt-marsh sediments. Agricultural occupation of saltmarshes and the later regeneration was recognised based on foraminifera and sand content. Saltmarshes in the eastern Cantabrian coast are expected to adapt to ongoing sea-level rise based on the high sedimentation rates (14-18 mm yr^{-1}) observed during the regeneration process of previously reclaimed areas. These findings can potentially be useful in other temperate saltmarshes with abundant sediment input, as a cost-effective adaptation measure to counteract the effects of sea-level rise.

Keywords: foraminifera, saltmarshes, reclamation, environmental management, N. Spain

1. Introduction

Since the late 19th century, the global population has quadrupled to nearly seven billion people (Bloom, 2011), hence shaping the natural environment. A new geological epoch has been proposed to describe the current human-dominated world, the Anthropocene (Crutzen and Stoermer, 2000). We have appropriated half the planet land surface for human uses (Kotchen and Young, 2007), such as agricultural occupation for food production and construction of cities. These land cover changes, combined with fossil fuel burning, have contributed to increasing concentrations of greenhouse gases in the atmosphere, causing a global surface temperature increase of 0.6 °C since the late 19th century (IPCC, 2014). This in turn has led to a global sea-level rise of 1.7±0.2 mm yr^{-1} during the period 1900-2009 (Church and White, 2011).

The current climatic scenario of global warming and accelerating sea-level rise represents a risk to the increasing proportion of people living in coastal areas (Neumann et al., 2015). Saltmarshes are considered geological archives of past environmental changes (Fatela et al., 2009), both natural and anthropogenic, and provide information to predict future trends of coastal evolution. These environments consist of vegetated gentle slopes and are found in all climate zones from the tropics to high-arctic coastal settings (Bartholdy, 2011). The elevation of these coastal areas varies as a result of accretion and compaction, the latter being more influential with the increasing age of the saltmarsh (van Wijnen and Bakker, 2001). Organic matter degradation can also affect salt-marsh elevation (Day et al., 2011; Kirwan and Blum, 2011). Both allochthonous (i.e. fluvial and marine detrital and organic sediments) and autochthonous (i.e. plant organic matter) sources supply sediments to saltmarshes (Allen, 2009), contributing to their vertical accretion. Some land use practices (e.g. agriculture and deforestation) in the upland can generate an important sediment source to coastal areas, and influence the sediment dynamics of saltmarshes (Kirwan et al., 2011; Tweel and Turner, 2012). The sediment load in the last several decades has been reduced in many rivers, and consequently in coastal wetlands, due to the proliferation of dams (Syvitski and Kettner, 2011).

Ongoing sea-level rise and decreasing sediment supplies to salt-marsh environments may lead to both major losses of this critical habitat and significant economic impacts. In fact, saltmarshes act to reduce wave energy, stabilising the shoreline and protecting coastal areas from storms and floods (Weis and Butler, 2009; Mudd et al., 2010). This acknowledgment of the importance of these coastal habitats has led to increased restoration of tidal marshes to help defend against ongoing sea-level rise as a consequence of current climate change (French, 2006; Roman and Burdick, 2012). This manipulation of the coast may be a cost-effective alternative, relative to constructed defence options, as an adaptation measure against ongoing sea-level rise (Turner et al., 2007), since saltmarshes accrete sediment to reach equilibrium with sea level (D'Alpaos et al., 2011).

The analysis of saltmarsh environmental regeneration is of particular interest in Spain where 44% of people live in coastal cities and towns that represent only 7% of the total national land area (Dias et al., 2013). This study focuses on the eastern Cantabrian coast (N. Spain), an area showing reclamation of more than 50% of the original saltmarshes (Gobierno Vasco, 1998). There are completely reclaimed estuaries converted to tidal channels, so that industrial activities and human settlements could expand (e.g. Suances: Irabien et al., 2008a; Bilbao: Cearreta et al., 2000; Plentzia: Cearreta et al., 2002 and Pasaia: Irabien et al., 2015). In contrast, there are also other estuaries that are preserved in their natural state, or at least apparently do not seem to have undergone significant anthropogenic alterations. This is the case of the Santoña estuary where we analysed two salt-marsh records. Results are compared with previous findings from another local saltmarsh (Leorri et al., 2014) and close-by studies developed in the presumably well-preserved Urdaibai estuary (Cearreta et al., 2013) and the canalised Plentzia estuary (Cearreta et al., 2002). The aim of this study is, therefore, to establish regional guidelines to recognise agricultural activities in the sedimentary records, as one of the main causes for disruption in saltmarshes from N. Spain (García-Artola, 2013), and the later environmental regeneration. To do that, we use an already validated combined micropalaeontological-geochemical approach (Cearreta et al., 2002, 2013). Short-lived radionuclides ^{210}Pb and ^{137}Cs, supported by historical aerial photography, are used to ascribe an age to the natural and anthropogenic processes.

For the first time, we provide a regional perspective in the analysis of saltmarsh reclamation and environmental regeneration, which has been so far based on isolated local studies. This in turn reinforces conclusions that can help local authorities to develop adaptation measures. This key information can also be very useful in coastal zones where historical aerial photography is not available or anthropogenic impacts occurred earlier than any historical record.

2. Regional setting

The eastern Cantabrian coast (N. Spain) is dominated by wave cut cliffs and marine terraces (Fig. 1). During the early Holocene, river valleys were drowned in response to the marine transgression that followed the last glacial maximum. This transgression caused inland migration of former coastal ecosystems, until ca. 8500 cal yr BP when the initial stages of modern estuaries developed (Leorri and Cearreta, 2004). Sea-level rise slowed down around 7000 cal yr BP and stabilised around 3000 cal yr BP, allowing the formation of modern saltmarshes (Leorri et al., 2012). Since the 17th century, these coastal wetlands have been reclaimed to carry out agricultural activities. This occupation was intense from the second half of the 19th century, and particularly when the Cambó Law was implemented in 1918 to promote desiccation of coastal wetlands due to their suspected insalubrity (Gogeascoechea and Juaristi, 1997). Since the agricultural decline during the 1950s, these previously reclaimed lands have been naturally regenerated and recolonised by halophytic vegetation. The lack of dyke maintenance allowed the entrance of estuarine water that invaded these once artificially isolated areas. This recovery of coastal wetlands can easily be observed in recent aerial photography (Chust et al., 2007). More recently, and in addition to reclamation for agricultural purposes, these coastal ecosystems have been occupied to support the urban and industrial settlements. Rivas and Cendrero (1991) conclude that human occupation of saltmarshes and other coastal intertidal areas represents the main geomorphological process in the southern Bay of Biscay during the last two centuries. The recognition of the ecological importance of coastal wetlands, has led local authorities to take political actions for their preservation during the last two decades. The Spanish Coastal Law, passed in 1988, included these coastal areas in the public domain, ultimately promoting their conservation.

In this sense, the Santoña saltmarshes (Fig. 1) were considered as a Nature Reserve in 1992 and they were designated as a Ramsar site in 1999. The estuary is formed by the tidal part of the Asón River and covers an area of 2000 ha; it is 11 km long and 0.5 km wide in the upper estuary and 3 km wide in the lower estuary (Cearreta, 1988). Approx. 63% of the total surface is exposed at low tide (Irabien et al., 2008b). The eastern bank of the lower estuary is dominated by sand, where beaches and sand dunes dominate. The western bank mainly accumulates muddy sediments and is dominated by saltmarshes. Along the eastern Cantabrian coast, the tidal regime is semidiurnal with a mean tidal range of 2.5 m; the minimum variation is 1 m (neap tides) and the maximum variation is 4.5 m (spring tides) (Monge-Ganuzas et al., 2013). The lower part of the estuary presents normal marine salinity values throughout the year (31-42 psu), while the salinity of the middle and upper sections of the system vary seasonally from 1-25 during winter to 27-40 during summer, essentially following rainfall regimes (Cearreta, 1988). See Cearreta et al. (2002, 2013) for details on the Plentzia and Urdaibai estuaries, respectively.

The Carasa saltmarsh is located at the confluence of the Rada and Limpias main channels (Fig. 1), in the upper part of the Santoña estuary. Historical aerial photography shows evidence of human impact (e.g. agricultural occupation) since at least the 1940s (Fig. 2). The Lastra saltmarsh is located on the west bank of the Boo channel (Fig. 1), in the lower part of the Santoña estuary. Historical aerial photography shows no evidence of human impact in the recent past (Fig. 2), hence a natural evolution of the saltmarsh at least during the time span between 1946 and 2011 was expected. Both saltmarshes are dominated by *Halimione portulacoides* and *Juncus maritimus* vegetation in the central part. See Cearreta et al. (2002, 2011, 2013) and Leorri et al. (2014) for description of the other saltmarshes in Fig. 1.

3. Material and Methods

Two cores were analysed in the present work (Fig. 1; yellow dots): one new core collected in 2011 (Lastra) and new analyses carried out on the formerly studied Carasa core, collected in 2010 (Irabien et al., 2015). Results are compared to previous analyses carried out in regional saltmarshes (Fig. 1; red dots).

3.1 Core extraction and geographical location

Cores were collected by hand by inserting two 50-cm long and 12.5-cm diameter PVC tubes into the central part of each saltmarsh. Core length at each site was dependent on the soil resistance with depth. Compaction of the sediment during the sampling process was negligible due to the detrital nature of regional sediments (Cearreta et al., 2002, 2013; Irabien et al., 2008b). At the same time, precise location and elevation of the cores was measured using a Global Positioning System-Real

Time Kinematic (GPS-RTK) and a total station, with a horizontal precision of ±20 mm and a vertical precision of ±35 mm. UTM coordinates (X, Y) were referred to the ED50 geographical system in planimetry and coordinate Z was referred to the local ordnance datum (LOD: lowest tide at the Bilbao Harbour on 27th September 1878) in altimetry. In the laboratory, each core (two replicates per site) was divided longitudinally in two halves, hence four identical halves were obtained from each saltmarsh sampled, each one used to carry out different analyses. Once visually described and photographed, each half was sliced into 1-cm sections.

3.2 Micropalaeontological analysis

Benthic foraminiferal abundance varies depending on environmental quality conditions (Cearreta et al., 2000). Extremely low numbers of foraminiferal tests have been found within agricultural deposits (Cearreta et al., 2002, 2013). Thus, foraminifera are a suitable proxy for the identification of such a human impact.

Core samples were analysed every two cm, except for the limits where samples were studied every one cm to provide the required resolution. Samples were washed through a 2 mm sieve in order to remove large organic fragments. The remaining material was then passed through a 63-μm sieve to remove fine-grained sediments and retain the sand size material containing foraminifera. After oven drying at 50 °C and weighed, samples were concentrated by flotation in trichloroethylene as described by Murray (1979). A representative number of 300 foraminiferal tests were extracted per sample unless fewer were present and then all the available tests were collected and studied under a stereoscopic binocular microscope using reflected light. Foraminiferal results are expressed as percentages and as number of foraminiferal tests per 50 g of bulk dry sediment for standardisation with regional values (Table 1). Cores were visually subdivided into depth intervals (DIs) based on the presence, abundance and dominance of foraminiferal species. The depositional environment of the identified DIs was interpreted by comparison with modern foraminiferal assemblages compiled by Cearreta et al. (2002) and Leorri et al. (2010). All foraminiferal species found in core samples are listed in Appendix 1.

3.3 Sand content analysis

The amount of sand in a sample is indicative of the tidal influence, which in turn declines during land reclamation (Cearreta et al., 2013). The sand to mud ratio was determined by weighing the dry sediment retained by the 63-µm sieve used for foraminiferal analysis. Results are presented as percentage of total dry weight.

3.4 Geochronology

The short-lived isotope ^{210}Pb (half-life 22.3 years) can be used to date sediments less than 150 years old (Appleby, 2001), the main time period of historical salt-marsh occupation in the eastern Cantabrian coast (Rivas and Cendrero, 1991). The ^{210}Pb-derived geochronology is usually validated through the artificial radionuclide ^{137}Cs (half-life 30 years), an independent time-stratigraphic marker of nuclear origin (Andersen et al., 2011).

Prior to laboratory analysis, sediment samples were oven dried at 60°C until constant weight. Dry bulk density and water content were then determined via weight loss. The Carasa core was analysed at the Universitat Autònoma de Barcelona (Spain). Total ^{210}Pb activities were determined, after total sample digestion, by alpha spectrometry of ^{210}Po in secular equilibrium (Sanchez-Cabeza et al., 1998). Excess ^{210}Pb (^{210}Pb$_{xs}$) was obtained by subtracting the ^{226}Ra activity (assumed to be equal to the supported ^{210}Pb activity), determined through ^{214}Pb in equilibrium by gamma spectrometry (351 keV emission line) from the total ^{210}Pb activity. ^{137}Cs activities were also determined by gamma spectrometry (661 keV) using a coaxial high-purity Germanium detector (EG&G Ortec). The Lastra core was analysed at the East Carolina University (Greenville, USA). ^{210}Pb measurements were carried out following the methodology described in Nittrouer et al. (1979) and ^{210}Pb$_{xs}$ activities were determined by subtracting the uniform ^{210}Pb background activity found at depth (Corbett et al., 2006). See for instance Zaborska et al. (2007) for an intercomparison of both methods.

The Constant Flux model (CF: Sanchez-Cabeza and Ruiz-Fernández, 2012; also known as the CRS model: Appleby and Oldfield, 1978) was applied to the Carasa core. This model assumes that the ^{210}Pb$_{xs}$ flux to the sediment surface is constant. The Simple model (Robbins, 1978) was applied to the Lastra core. This model assumes a constant ^{210}Pb$_{xs}$ flux to the sediment surface and a constant mass sedimentation rate.

3.5 Geochemical analysis

In combination with foraminiferal analysis, heavy metals, as pollution indicators, have been shown to be useful for the study of salt-marsh occupation and environmental regeneration (Cearreta et al., 2002, 2013). Heavy metal content analysis was performed by Activation Laboratories Ltd. (Ontario, Canada) by Inductively Coupled Plasma-Optic Emission Spectrometry (ICP-OES) after digestion with aqua regia as described in Cearreta et al. (2013). The four relevant heavy metals (Cu, Ni, Pb and Zn), according to previous studies in the region (Irabien and Velasco, 1999; Cearreta et al., 2002; Irabien et al., 2008b), and Al are presented. Detection limits were 0.01% for Al, 1 mg kg^{-1} for Cu, Ni and Zn, and 2 mg kg^{-1} for Pb. Although grain size is fairly constant throughout the Carasa and Lastra cores, metal concentrations are normalised using Al (Ackermann, 1980; Mil-Homens et al., 2006) to be compared with previous regional studies (Cearreta et al., 2002, 2013). Aluminium shows a very close relationship with K and Sc (r>0.89) and it is used as a proxy of the clay fraction (Cearreta et al., 2013).

4. Results

4.1 Carasa core

The core (coordinates X: 462,590.847, Y: 4,803,949.206, Z: 3.067 m above LOD) was made of light brown coloured mud in the upper 23 cm (with plant roots in the upper 10 cm) and the lower 27 cm were characterised by dark grey mud (Fig. 3). The abundance of benthic foraminifera was high in the upper 41 cm and low in the rest of the core. In total, 28 samples, 6230 foraminiferal tests and 11 species were analysed (Appendix 2). Following Irabien et al. (2015), the core was divided in three depth intervals (DIs: Table 2; Fig. 3). The lowermost 9 cm (DI3) were represented by very low numbers of foraminiferal tests (mean 40 tests/50 g). *Entzia macrescens* and *Trochammina inflata* were the main species in this interval (percentages were not produced due to the low numbers of foraminiferal tests present in the samples). Species number (average 3 species) was very low. The following 18 cm (DI2) were characterised by low and upward-increasing numbers of foraminiferal tests (mean 230 tests/50 g), dominated by *E. macrescens* (average 70%) and *T. inflata* (average 28%). Like previous DI3, species number (average 3 species) was very low. The uppermost 23 cm (DI1) showed high numbers of foraminiferal tests (mean 3416 tests /50 g), dominated by *E. macrescens* (average 67%) and *T. inflata* (average 27%). *Haplophragmoides wilberti* (average 4%) and *Arenoparrella mexicana* (average 2%) appeared as secondary forms. Species number (average 5 species) was low, although slightly higher than in the precedent DIs.

Sediments in this core were almost entirely composed of mud (Table 2; Fig. 3), with an average sand content of 1% throughout. Regarding to short-lived radioisotope activities, the Carasa $^{210}Pb_{xs}$ profile shows a typical exponential decay and suggests that a ^{210}Pb-derived chronology would be feasible (Fig. 3). Moreover, the ^{137}Cs activity peak was identified at 23 cm depth, in the limit between DI1 and DI2. The average and range of Cu, Ni, Pb and Zn concentrations (n=25) are shown in Table 2. Vertical distribution of concentrations and Al-normalised vertical profiles are very similar, so only the latter ones are represented in Fig. 3. Low and fairly constant heavy metal values were observed in DI3. Pb and Zn increased from the bottom of DI2 up to the bottom centimetres of DI1 (especially Zn), where they reached maximum levels. A decreasing trend was observed until 10 cm depth, followed by moderately constant values in topcore samples. Cu and Ni showed little variation.

4.2 Lastra core

The core (coordinates X: 461,811.405, Y: 4,811,193.003, Z: 3.189 m above LOD) was composed primarily of brown mud and abundant organic matter in the upper 27 cm, and grey mud with less organic matter in the lower 23 cm (Fig. 4). Benthic foraminiferal content was high in the upper 22 cm and the lowermost 8 cm, while it was very low in the intermediate interval. In total, 26 samples, 4581 foraminiferal tests and 5 species were analysed (Appendix 2). Three DIs were distinguished in the core (Table 2; Fig. 4). The lower 8 cm (DI3) showed moderate numbers of foraminiferal tests (mean 407 tests /50 g) and species number was very low (2 species). *Entzia macrescens* (average 76%) and *T. inflata* (average 24%) were the only species found in this interval. The following 20 cm (DI2) were characterised by very low numbers of foraminiferal tests (mean 66 tests /50 g). The number of extracted foraminifera was not enough to calculate relative abundances, but *E. macrescens* and *T. inflata* were present, similar to the lower interval. Species number (average 2 species) was very low. The top 22 cm (DI1) had very high number of foraminiferal tests (mean

15,643 tests/50 g). This interval was dominated by *E. macrescens* (average 53%) and *T. inflata* (average 45%). *Arenoparrella mexicana* (average 2%) appeared as a secondary species. Species number (average 4 species) was very low, but slightly higher than in the lower intervals.

As in the Carasa core, sand content was low throughout (average 2%; see Table 2 and Fig. 4). The first appearance of $^{210}Pb_{xs}$ and ^{137}Cs was at 32 (DI2) and 16 (DI1) cm, respectively. The ^{137}Cs activity peak was found at 11 cm depth in DI1 (Fig. 4). The average and range of Cu, Ni, Pb and Zn (n=30) concentrations are shown in Table 2. In general, Al-normalised vertical profiles (as metal concentrations; Table 2) showed low and rather constant values up to the middle of DI2, where Pb and Zn start to increase (Fig. 4). Maximum values were found around 7 cm depth, generally lowering down towards the surface. Abundance of Cu and Ni showed very small changes.

5. Discussion

5.1 Interpretation of the Carasa core

The near absence of foraminifera found in DI3 is unusual in regional intertidal areas and can be attributed to the anthropogenic deposit introduced during agricultural reclamation as indicated by aerial photography (Fig. 2). DI2 was interpreted as being deposited during the regeneration process; as tidal waters invaded the formerly occupied saltmarsh, the abundance of benthic foraminifera increased. The presence of the highest foraminiferal abundances in the top interval (DI1) indicates the stabilisation of this regenerated high salt-marsh environment. Although DI1 in Carasa presented a few calcareous tests, typically associated with low saltmarshes and/or tidal flats, they are commonly preserved in high saltmarsh settings of the eastern Cantabrian coast because regional fluvial waters seem to be saturated in calcium carbonate (Cearreta and Murray, 2000). Therefore, the presence of calcareous tests in the core is related to its increased preservation and does not appear related to a low marsh setting.

Sand content results indicate that the area represented a low energy environment from the human occupation period (DI3) until the regenerated high salt-marsh environment (DI1) was developed. A slight increase in sand content is observed from the bottom to the top of the core, which could be related to the entrance of sand-rich estuarine water as regeneration took place.

The ^{210}Pb-derived chronology (Fig. 3) based on the CF model (Sanchez-Cabeza and Ruiz-Fernández, 2012) suggests that in 1945 the saltmarsh was already regenerated (DI1), but this contradicts aerial photography that clearly shows agricultural land in this area at that time (Irabien et al., 2015). However, the profile displayed by ^{137}Cs offers an alternative time frame. As the eastern Cantabrian coast is far from major nuclear facility discharges (e.g. Sellafield, Cap La Hague) and the influence of the Chernobyl plume, the ^{137}Cs peak is most likely related to peak nuclear weapons testing in 1963 (Irabien et al., 2008a). In this core, the assignment of this date to the limit between DI1 and DI2 seems to be in good agreement with metal profiles (Fig. 3), given that Irabien at al. (2008b) traced back the beginning of Zn and Pb enrichment in sediments collected in a nearby core to the 1960s.

According to aerial photography and the ^{137}Cs peak, the regeneration process in the Carasa saltmarsh took around 10 years. Areas that appeared cultivated in the late 1940s were already undistinguishable from other surrounding salt-marsh areas by the early 1970s, corroborated by the 1963 ^{137}Cs peak (Irabien et al., 2015). Based on these ages and the DIs thickness, we can infer that sedimentation rates during the regeneration process (DI2) could have reached 18 mm yr^{-1}, and were reduced to 5 mm yr^{-1} once the saltmarsh was regenerated (DI1). This is supported by the Al-normalised Zn and Pb profiles (Fig. 3), which show enhanced values in DI2 corresponding to the initial stages of pollution in the estuary (1960s; Irabien et al., 2008b) that peak slightly above the bottom of DI1. In fact, according to the proposed chronology, highest values of Pb should be associated with the mid-1970s, coinciding with maximum Pb emissions to the atmosphere in Europe (Pacyna et al., 2007). The initial disagreement between the ^{210}Pb-derived chronology and the historical records could be explained on the basis of a missing sediment segment (i.e. a hiatus), leading to a lower measured whole core ^{210}Pb inventory (Appleby, 2001). It is possibly the case when comparing the bottom value (ca. 32 Bq kg^{-1}; Fig. 3) with that found in the nearby Lastra core (approx. 16 Bq kg^{-1}), indicating that background ^{210}Pb activities were not reached in the Carasa core. Similar examples of disagreement with aerial photography and other chronological markers have been reported in the region (Cearreta et al., 2002; Leorri et al., 2013). When a missing inventory of 1760

Bq m^{-2} was used in the CF model, the saltmarsh would have established in 1969, in good agreement with aerial photography and the ^{137}Cs peak. This further emphasises the need for independent chronological markers when interpreting sedimentary records from anthropogenically-disturbed areas.

5.2 Interpretation of the Lastra core

The lower DI3 interval represents the original high salt-marsh environment. The near absent foraminifera at the bottom and the low numbers towards the top of DI2 represent the agricultural occupation followed by the regeneration process. It is likely that there is no clear separation between these two events due to mixing of materials within this interval during the regeneration process. The uppermost DI1 interval is indicative of the modern regenerated high salt-marsh environment.

Sand content indicates a low energy environment prior to the occupation period (lower DI2), until the regenerated high salt-marsh environment (DI1) was developed. At closer inspection, low sand content in the lower DI2 increases upwards as tidal waters invaded the formerly reclaimed saltmarsh during environmental regeneration.

Downcore ^{210}Pb-derived sample ages obtained via the Simple model (Robbins, 1978) are in good agreement with the ^{137}Cs 1963 peak. The inferred sedimentation rate for the top 22 cm is 2.1±0.1 mm yr^{-1}, similar to the sea-level rise rate reconstructed for the 20th century in the eastern Cantabrian coast (Leorri et al., 2008; García-Artola et al., 2009). Based on this chronology, the saltmarsh was already established by the 1910s (Fig. 4). Assuming 10 years for the regeneration process (as suggested above for Carasa but also other regional sites; e.g. Cearreta et al., 2013), the agricultural use of this area was abandoned by the turn of the 20th century, and based on the fact that the main agricultural period in the Cantabrian estuaries was between 1875 and 1925 (Rivas and Cendrero, 1991), lower DI2 (e.g. agricultural occupation period) most likely encompasses between 1875 and 1900.

According to the ^{210}Pb-derived ages, Zn and Pb enrichment in the Lastra saltmarsh seems to have started prior to the 1910s, at the middle of the regeneration period. However, in surface samples (~10 cm), corresponding to the last ca. 50 years, distribution of Pb is pretty similar to that found in

Carasa (with maximum values at about 1977 and decreasing trends afterwards) and in other cores collected in this estuary (Irabien et al., 2008b; Leorri et al., 2014).

5.3 Regional overview

Anthropogenically-modified saltmarshes via agricultural reclamation present sudden, interruptions in their natural salt-marsh sedimentation rates reflected in the geological record. These human interventions need to be considered when palaeoenvironmental reconstructions are developed using salt-marsh sedimentary records (e.g. reconstructions of past sea levels). If we take into account new results from the present work and previous regional studies (see Fig. 1 for location and Table 3 for summary results), we observe that a few guidelines characterise the agricultural reclamation and later regeneration of saltmarshes from the eastern Cantabrian coast regarding benthic foraminifera, sand and heavy metal contents, short-lived radioisotope activities and historical aerial photography.

The identification of agricultural soils in salt-marsh sedimentary records is based on the near absence of foraminifera, which is unusual in this area of study and has been related to low oxygen conditions as a consequence of anthropogenic environmental pollution (Cearreta et al., 2000). Attributing agricultural occupation to the extremely low foraminiferal densities observed in the basal depth intervals is mainly due to the availability of aerial photography, which provides a documentary record of those activities in this (Carasa saltmarsh; Irabien et al., 2015) and nearby estuaries (Cearreta et al., 2002, 2013). There is a general pattern (Pattern 1 in Table 3) observed in the foraminiferal content evolution from regenerated saltmarshes in N. Spain estuaries: near absent foraminifera in DI3, upward-increasing foraminifera in DI2 and abundant foraminifera in DI1. Leorri et al. (2014) noted that this pattern can be used to identify reclamation in sedimentary records where this activity is not recorded in historical aerial photography, since it occurred prior to 1946 (age of the first aerial photography available for this area). Rivas and Cendrero (1991) pointed out that the process of filling and reclamation of saltmarshes in the Cantabria province was particularly intense during the period 1875-1925. In general, we observe that foraminiferal densities increase upwards an order of magnitude each interval. In the Escalante core (Table 3; Fig. 1; Leorri et al., 2014), the difference is even greater, which could be related to the fact that this saltmarsh was occupied by human activities earlier than the other saltmarshes. In fact, there is no evidence of agricultural occupation in the aerial photography since 1946 (Leorri et al., 2014). Escalante has behaved as a regenerated stable saltmarsh for a long time period and, as a result, foraminifera are more abundant. In fact, the foraminiferal density in DI1 is more similar to the abundances observed in regional saltmarshes that have experienced a natural evolution (e.g. Murueta saltmarsh from the nearby Urdaibai estuary; García-Artola et al., 2015).

A second pattern regarding foraminiferal distribution (Pattern 2 in Table 3) and related to regenerated saltmarshes occurs when we can identify the former original saltmarsh such as DI3 in the Lastra core. Similar profiles have been previously identified in the Baraizpe (Table 3; Fig. 1; Cearreta et al., 2013) and Txipio (Table 3; Fig. 1; Cearreta et al., 2002, 2011) saltmarshes from the nearby Urdaibai and Plentzia estuaries respectively, which present historical records of agricultural occupation, so we can attribute the pattern in Lastra to that human activity.

Sand profiles contribute to the foraminifera-based identification of the anthropogenic impact, reflected on increasing amounts of this proxy during the regeneration process (DI2: Table 3). Immediately after reclamation ends sand-rich tidal waters invade the originally occupied saltmarshes (although sand patterns from Carasa and Lastra are not so obvious).

Recently regenerated (post-1950s) saltmarshes present challenges in ^{210}Pb dating techniques due to the physical disturbance caused by agricultural soils (e.g. missing ^{210}Pb inventories and mixing of sediments), even with a typical exponential decay profile (Cearreta et al., 2002; Leorri et al., 2014). In this case, independent markers such as ^{137}Cs, aerial photography and heavy metal profiles, as indicators of historical pollution, are indispensable tools for age determination and estimation of sedimentation rates. From a regional perspective, the regeneration of the saltmarshes took place over a range in time (Table 3). The Urdaibai estuary salt-marsh regeneration occurred between the 1950s and 1960s. The Plentzia estuary regeneration occurred from the 1970s-1980s and beyond. The Santoña estuary regeneration took place between the 1950s and 1960s. However, regeneration in some areas may have occurred much earlier, even before the 1940s. In all locations, the regeneration process was very rapid (generally less than 10 years; Table 3), due to high sedimentation rates, determined from the sediment thickness and the age of the boundaries between DIs, during the regeneration process (14-18 mm yr^{-1}; DI2) compared to the regenerated saltmarsh (0.9-5 mm yr^{-1}; DI1). The observed high sedimentation rates during the regeneration process are due to the abundant availability of detrital material in regional estuaries that enables the infill of the area, leading to a higher elevation and the reduction of the tidal flooding (Cearreta et al., 2002). Once sufficient elevation is reached in relation to the tidal frame, recolonisation by vegetation occurs and enhances sediment trapping (Friedrichs and Perry, 2001). The regenerated saltmarsh continues to develop under lower sedimentation rates, although full restoration of natural functions often takes longer (Hazelden and Boorman, 2001). Differences in sedimentation rates between saltmarshes seem to be related to the location within the estuary (Fig. 1). While more isolated saltmarshes, such as Baraizpe or Lastra, present lower sediment accumulation rates, saltmarshes next to channels, such as Carasa or Busturia, tend to have higher sediment accumulation rates (Table 3).

The utility of heavy metals as reclamation and regeneration indicators was proposed by Cearreta et al. (2013), indicated by their dilution during the regeneration process. Analyses from the Carasa and Lastra cores do not corroborate those results (Figs. 3 and 4), showing heavy metal enhancement during the regeneration process. Therefore, it is essential to rely on multiple cores from the same and close-by estuaries for comparisons. Heavy metals have proven to benefit the age determinations independently determined by ^{210}Pb, as chronostratigraphic horizons of major pollution events.

To summarise, agricultural soils can be identified by the nearly absence of foraminifera, saltmarshes under environmental regeneration show increasing amounts of foraminifera and sand, and very high sedimentation rates, and regenerated environments present abundant foraminifera and enrichment of heavy metals, indicating recent pollution histories. Sediment availability has been crucial in the region for the environmental regeneration of previously reclaimed saltmarshes, and hence adaptation to sea-level rise. Similarly, sediment supply seems to constrain the development of regeneration in North America (Williams and Faber, 2001) and Europe (Wolters et al., 2005). In areas with a limited supply of sediment, a reduced tidal regime is advisable to obtain a partially vegetated tidal marsh (Vandenbruwaene et al., 2012).

6. Conclusions

Anthropogenic activities influence the natural sedimentation regime of saltmarshes. While metals and short-lived radio-isotopic profiles do not always show clear patterns that could help to identify these interruptions, foraminiferal distributions and sand content are excellent proxies.

In the current context of climate change and sea-level rise, coastal areas, which are highly populated and economically essential, are prone to erosion and flooding. Therefore, saltmarshes are threatened environments unless they receive sufficient sediment supply to keep pace with the rate of sea-level rise. These systems offer a natural protection in coastal areas, and their loss would increase the likelihood of erosion and flooding of the coast. In order to make predictions of future habitat change of these coastal zones, it is important to understand their environmental evolution in the recent past. Saltmarshes in the eastern Cantabrian coast (N. Spain) are expected to keep pace with ongoing sea-level rise taking into account the high sedimentation rates (14-18 mm yr^{-1}) observed during the regeneration process. The restoration of currently reclaimed tidal wetlands can serve as a cost-effective and fast response (~10 years) adaptation strategy against climate change consequences on this coastal zone, which is also of applicability in other temperate saltmarshes with abundant sediment input.

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Appendix 1. Microfaunal reference list from regenerated saltmarshes in the eastern Cantabrian coast (N. Spain) (online at doi:XXX)

Appendix 2. Complete foraminiferal census data, sand content, heavy metal concentrations and geochronology results from regenerated saltmarshes in the eastern Cantabrian coast (N. Spain) (online at doi:XXX)

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Figure captions

Figure 1. Geographical location of the Santoña (1), Plentzia (2) and Urdaibai (3) estuaries in the eastern Cantabrian coast (N. Spain) where first time (yellow dots) and formerly (red dots) studied cores, and other localities mentioned in the text are represented.

Figure 2. Location of the Carasa and Lastra cores (red dots) in historical (1946: left side) and modern (2011: right side) aerial photographs.

Figure 3. Core photograph, sand content (%), main foraminiferal species (1: *E. macrescens*; 2: *T. inflata*; 3: *A. mexicana*; 4: *H. wilberti*) (%), foraminiferal density/50 g of bulk dry sediment, $^{210}Pb_{xs}$ and ^{137}Cs activities (Bq kg^{-1}) and Al-normalised Cu, Ni, Pb and Zn distribution with depth (cm) in the Carasa core. Ages based on the CF model, the ^{137}Cs peak and aerial photography (in a box) are shown. DI: depth interval.

Figure 4. Core photograph, sand content (%), main foraminiferal species (1: *E. macrescens*; 2: *T. inflata*; 3: *A. mexicana*) (%), foraminiferal density/50 g of bulk dry sediment, $^{210}Pb_{xs}$ and ^{137}Cs activities (Bq kg^{-1}) and Al-normalised Cu, Ni, Pb and Zn distribution with depth (cm) in the Lastra core. Ages based on the Simple model and the ^{137}Cs peak are shown. DI: depth interval.

Table captions

Table 1. Foraminiferal quantification of absolute and relative abundances of tests and species for estuaries of the eastern Cantabrian coast (N. Spain).

Table 2. Summary of lithological, microfaunal and raw metal concentration data in the Carasa and Lastra cores (Santoña estuary). The single value represents the average and those in parentheses give the range. All metal concentration values in mg kg^{-1}. <DL: below detection limit.

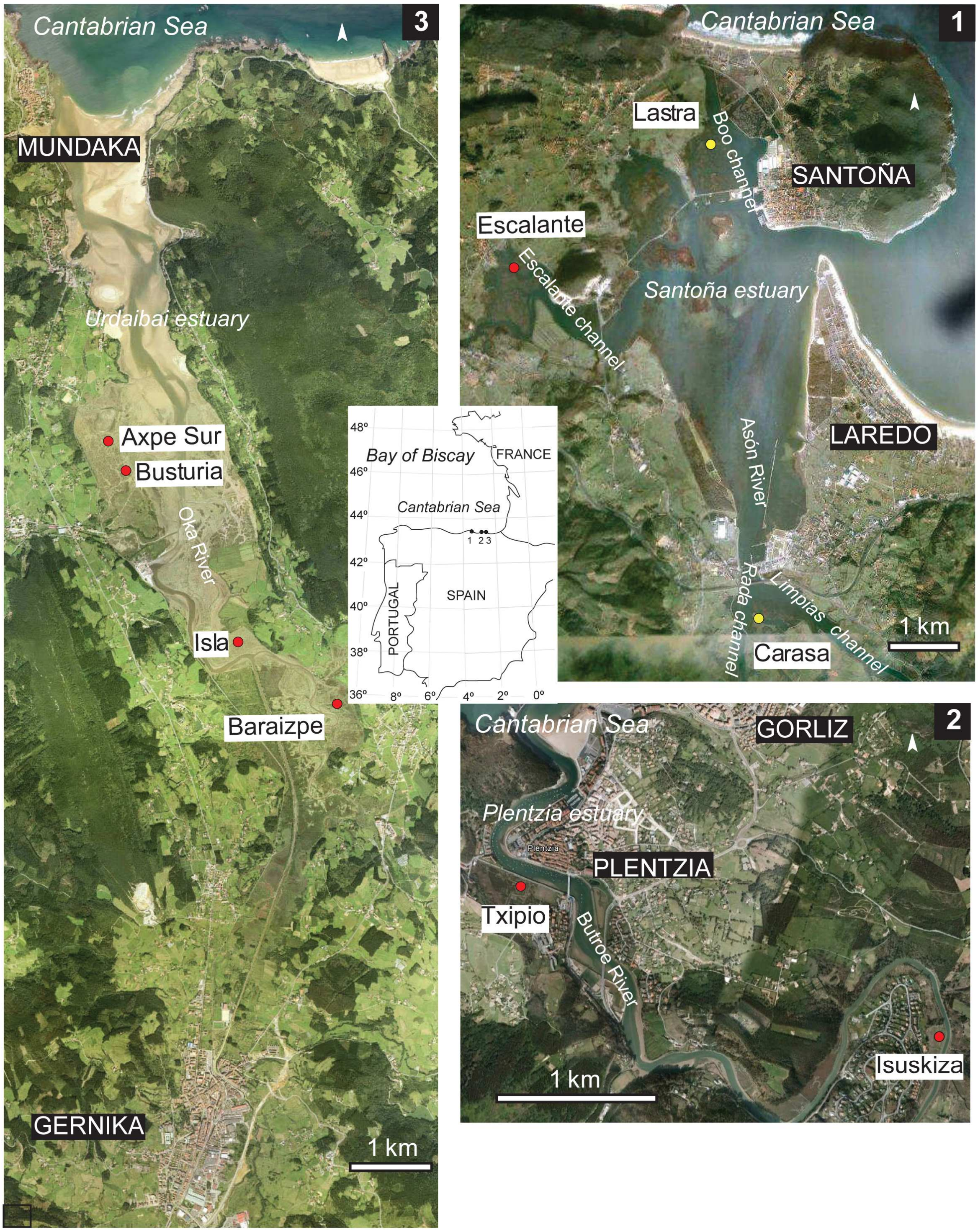
Table 3. Summarised results of reclamation and later environmental regeneration in salt-marsh sedimentary records from the eastern Cantabrian coast (N. Spain). fd: foraminiferal density; f: foraminifera.

Abundance	Very low	Low	Moderate	High	Very high
Number of tests/50 g	<100	100-300	300-2000	2000-5000	>5000
Number of species	<5	5-10	10-20	20-30	>30
% Allochthonous tests	<20	20-40	40-60	60-80	80-100
Dominant species	>10%				
Secondary species	2-10%				
Minor species	<2%				

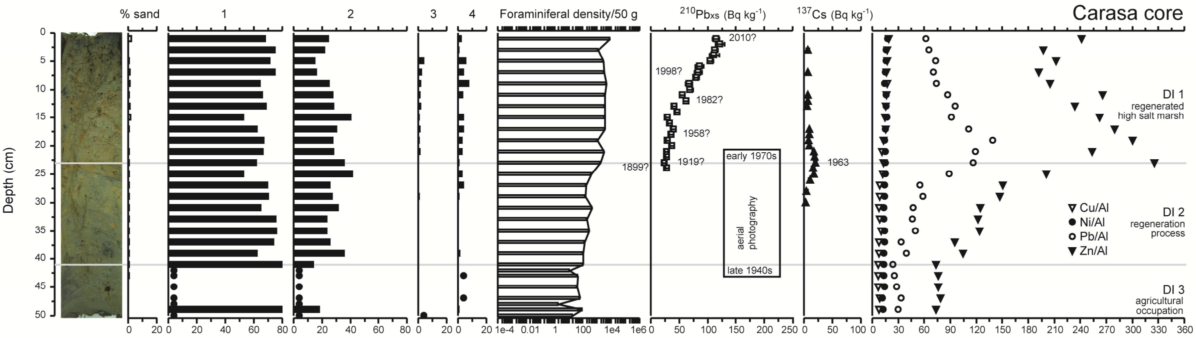
DI1: regenerated high salt marsh Thickness: 23 cm Elevational range: 3.067-2.837 m Lithology: light brown mud with plant roots in the upper 10 cm 1 (1-3)% sand 3416 (1110-8189) tests 5 (3-7) species *E. macrescens* 67 (53-75)% *T. inflata* 27 (16-41)% *H. wilberti* 4 (0-8)% *A. mexicana* 2 (0.3-4)% Cu 16 (13-18) Ni 17 (15-18) Pb 96 (59-157) Zn 256 (193-371)	DI1: regenerated high salt marsh Thickness: 22 cm Elevational range: 3.189-2.969 m Lithology: brown mud with abundant plant roots 2 (0-3)% sand 15,643 (3925-28,100) tests 4 (2-4) species *E. macrescens* 53 (18-79)% *T. inflata* 45 (21-81)% *A. mexicana* 2 (0-4)% Cu 14 (10-28) Ni 16 (12-35) Pb 83 (54-175) Zn 195 (146-376)
DI2: regeneration process Thickness: 18 cm Elevational range: 2.837-2.657 m Lithology: dark grey mud 1% sand 230 (107-492) tests 3 (2-6) species *E. macrescens* 70 (53-86)% *T. inflata* 28 (14-42)% Cu 11 (9-13) Ni 17 (16-19) Pb 59 (32-99) Zn 152 (97-223)	DI2: agricultural occupation & regeneration process Thickness: 20 cm Elevational range: 2.969-2.769 m Lithology: dark grey mud, browner and organic richer to the top 2 (1-3)% sand 66 (5-199) tests 2 (2-3) species Few foraminifera Cu 9 (8-10) Ni 15 (14-17) Pb 42 (28-75) Zn 104 (72-139)
DI3: agricultural occupation Thickness: 9 cm Elevational range: 2.657-2.567 m Lithology: dark grey mud 1 (0-1)% sand 40 (2-96) tests	DI3: original high salt marsh Thickness: 8 cm Elevational range: 2.769-2.689 m Lithology: dark grey mud 2% sand 407 (120-1193) tests

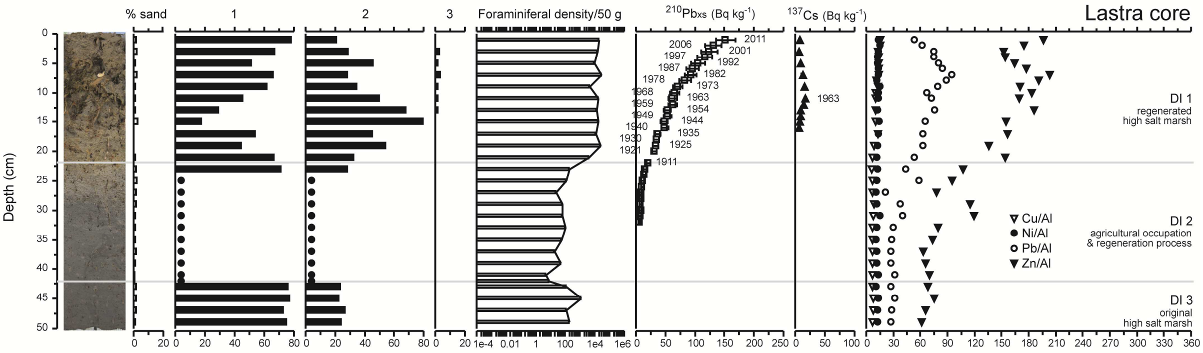
3 (2-4) species	2 species
Few foraminifera	*E. macrescens* 76 (73-77)%
	T. inflata 24 (23-27)%
Cu 10 (9-11)	Cu 8 (8-9)
Ni 18 (16-19)	Ni 15 (14-15)
Pb 39 (33-44)	Pb 34 (33-34)
Zn 100 (96-102)	Zn 79 (73-83)

RECLAMATION	ESTUARY	CORE	DIs	THICKNESS	FORAMINIFERA	SAND	CHRONOLOGY		SED. RATE	HEAVY METALS		ENVIRONMENT	SOURCE
Pattern 1	Santoña	Carasa	DI1	23 cm	fd/50 g: 3416 tests	stabilised content (1%)	aerial photography		5 mm yr^{-1}	enrichment		regenerated high salt marsh	Irabien et al. (2015)
			DI2	18 cm	fd/50 g: 230 tests	upwards increasing (1%)		1950s-1960s	18 mm yr^{-1}	enrichment	since 1950s	regeneration process	This work
			DI3	9 cm	fd/50 g: 40 tests	lowest content (1%)						agricultural occupation	
		Escalante	DI1	9 cm	fd/50 g: 39,350 tests	stabilised content (3%)	aerial photography			enrichment		regenerated high salt marsh	Leorri et al. (2014)
			DI2	21 cm	fd/50 g: 2410 tests	upwards increasing (2%)				enrichment	prior to 1940s	regeneration process	
			DI3	16 cm	fd/50 g: 53 tests	lowest content (1%)		prior to 1940s				agricultural occupation	
	Plentzia	Isuskiza	DI1	7 cm	fd/50 g: 632 tests	stabilised content (35%)	aerial photography			enrichment	since 1960s	regenerated low salt marsh	Leorri et al. (2013)
			DI2	34 cm	fd/50 g: 39 tests	upwards increasing (34%)		since 1970s-1980s	14-17 mm yr^{-1}			regeneration process	Cearreta et al. (2011)
			DI3	9 cm	fd/50 g: 0 tests	lowest content (12%)						agricultural occupation	
	Urdaibai	Axpe Sur	DI1	5 cm	fd/50 g: 5561 tests	stabilised content (7%)	no possible dating			enrichment	since 1960s	regenerated low salt marsh	Leorri et al. (2014)
			DI2	21 cm	fd/50 g: 463 tests	upwards increasing (3%)	through ^{210}Pb and ^{137}Cs					regeneration process	
			DI3	14 cm	fd/50 g: 19 tests	lowest content (3%)	nor aerial photography					agricultural occupation	
		Busturia	DI1	19 cm	f analysed: 306 tests	stabilised content (12%)	aerial photography		3.5 mm yr^{-1}	enrichment	since 1960s	regenerated low salt marsh	Cearreta et al. (2013)
			DI2	8 cm	f analysed: 31 tests	upwards increasing (8%)	and ^{137}Cs	1950s-1960s	14 mm yr^{-1}			regeneration process	
			DI3	10 cm	f analysed: 2 tests	lowest content (1%)						agricultural occupation	
		Isla	DI1	13 cm	fd/50 g: 5635 tests	stabilised content (16%)	aerial photography		1.7 mm yr^{-1}	enrichment	since 1960s	regenerated low salt marsh	Cearreta et al. (2013)
			DI2	19 cm	fd/50 g: 1317 tests	upwards increasing (13%)	and ^{137}Cs	1950s-1960s	18 mm yr^{-1}			regeneration process	
			DI3	12 cm	fd/50 g: 31 tests	lowest content (5%)						agricultural occupation	
Pattern 2	Santoña	Lastra	DI1	22 cm	fd/50 g: 15,643 tests	stabilised content (2%)	^{210}Pb and ^{137}Cs		2.2 mm yr^{-1}	enrichment		regenerated high salt marsh	This work
			DI2	20 cm	fd/50 g: 66 tests	lowest content (2%)		1900s-1910s (regeneration)		enrichment	between 1900s-1910s	agricultural and regeneration process	
			DI3	8 cm	fd/50 g: 407 tests	moderate content (2%)						original high salt marsh	
	Plentzia	Txipio	DI1	1 cm	fd/50 g: 704 tests	stabilised content (4%)				enrichment	after late 1960s	low salt marsh in regeneration	Cearreta et al. (2002)
			DI2	7 cm	fd/50 g: 81 tests	lowest content (6%)	aerial photography	since 1860-late 1960s	0.5-1 mm yr^{-1}	enrichment (upper half)		agricultural occupation	Cearreta et al. (2011)
			DI3	5 cm	fd/50 g: 941 tests	high content (29%)						original low salt marsh	
			DI4	17 cm	fd/50 g: 1166 tests	high content (37%)						tidal flat	
	Urdaibai	Baraizpe	DI1	5 cm	fd/50 g: 1222 tests	stabilised content (9%)	aerial photography		0.9 mm yr^{-1}	enrichment	since 1960s	regenerated low salt marsh	Cearreta et al. (2013)
			DI2	4 cm	fd/50 g: 44 tests	lowest content (1%)	and ^{137}Cs	1950s-1960s (regeneration)				agricultural and regeneration process	
			DI3	15 cm	fd/50 g: 304 tests	moderate content (2%)						original high salt marsh	


Cantabrian Sea
3
MUNDAKA
Urdaibai estuary
Axpe Sur
Busturia
Oka River
Isla
Baraizpe
GERNIKA
1 km
Cantabrian Sea
1
Lastra
Boo channel
SANTOÑA
Escalante
Escalante channel
Santoña estuary
LAREDO
Asón River
Rada channel
Limpias channel
Carasa
1 km
48º
46º
44º
42º
40º
38º
36º
8º
6º
4º
2º
0º
Bay of Biscay
FRANCE
Cantabrian Sea
1 2 3
SPAIN
PORTUGAL
Cantabrian Sea
GORLIZ
2
Plentzia estuary
Plentzia
PLENTZIA
Txipio
Butroe River
Isuskiza
1 km


CARASA
1946
2011
200 m
LASTRA
1946
2011
200 m


Carasa core
Depth (cm)
0
5
10
15
20
25
30
35
40
45
50
% sand
0 20
1
0 20 40 60 80
2
0 20 40 60 80
3
0 20
4
0 20
Foraminiferal density/50 g
1e-4 0.01 1 100 1e4 1e6
^{210}Pb$_{xs}$ (Bq kg^{-1})
0 50 100 150 200 250
2010?
1998?
1982?
1958?
1919?
1899?
early 1970s
aerial photography
late 1940s
^{137}Cs (Bq kg^{-1})
0 50 100
1963
0 30 60 90 120 150 180 210 240 270 300 330 360
Cu/Al
Ni/Al
Pb/Al
Zn/Al
DI 1
regenerated high salt marsh
DI 2
regeneration process
DI 3
agricultural occupation


Lastra core
Depth (cm)
0
5
10
15
20
25
30
35
40
45
50
% sand
0 20
1
0 20 40 60 80
2
0 20 40 60 80
3
0 20
Foraminiferal density/50 g
1e-4 0.01 1 100 1e4 1e6
^{210}Pbxs (Bq kg^{-1})
0 50 100 150 200 250
2011
2006
2001
1997
1992
1987
1982
1978
1973
1968
1963
1959
1954
1949
1944
1940
1935
1930
1925
1921
1911
^{137}Cs (Bq kg^{-1})
0 50 100
1963
0 30 60 90 120 150 180 210 240 270 300 330 360
Cu/Al
Ni/Al
Pb/Al
Zn/Al
DI 1
regenerated
high salt marsh
DI 2
agricultural occupation
& regeneration process
DI 3
original
high salt marsh

Highlights

Criteria to identify records of agricultural activities in saltmarsh sediments are shown.

Benthic foraminifera and sand content are appropriate proxies to recognise this disturbance.

Recently regenerated saltmarshes present difficulties to reconcile ^{210}Pb dating.

Regional sediment availability is fundamental for the environmental regeneration.

Saltmarshes in N. Spain are expected to adapt to ongoing sea-level rise.