Environmental controls on carbon sequestration, sediment accretion, and elevation change in the Ebro River Delta: Implications for wetland restoration

Authors
M, Siobhan Fennessy[1]
Carles Ibáñez[2]
Juan Calvo-Cubero[3]
Peter Sharpe[4]
Albert Rovira[2]
John Callaway[5, 6]
Nuno Caiola[2]

[1]Kenyon College, Biology Department, Gambier, OH 43022 USA
[2]IRTA, Aquatic Ecosystems Program, 43540 Sant Carles de la Ràpita Catalonia, Spain
[3]Catalan Water Agency (ACA), Barcelona, Catalonia, Spain.
[4]The National Park Service, Natural Resources Science and Stewardship, 423 Forest Resources Building, University Park, PA USA 16802
[5]San Francisco State University, Department of Environmental Science, 2130 Fulton St., San Francisco, CA 94117 USA
[6]current address: Delta Science Program, 980 Ninth St., Suite 1500, Sacramento, CA 95814 USA

M. S. Fennessy Corresponding Author:
fennessym@kenyon.edu
Phone: +1-740-427-5455
Fax: +1-740-427-5741

ABSTRACT

Delta wetlands are increasingly recognized as important sinks for 'blue carbon,' although this and other ecosystem services that deltas provide are threatened by human activities. We investigated factors that affect sediment accretion using short term (3 years using marker horizons) and longer-term measures (~50 year using ^{137}Cs soil core distribution and ~100 year using ^{210}Pb distribution), the associated carbon accumulation rates, and resulting changes in surface elevation in the Ebro River Delta, Catalonia, Spain. Fifteen sites were selected, representing the geomorphological settings and range of salinities typical of the delta's wetlands. Sediment accretion rates as measured by ^{137}Cs distribution in soil cores ranged from 0.13 to 0.93 cm yr^{-1}. Surface elevations increased at all sites, from 0.10 to 2.13 cm yr^{-1} with the greatest increases in natural impoundments with little connection to other surface waters. Carbon accumulation rates were highly spatially variable, ranging from 32 to 435 g C m^{-1} yr^{-1} with significantly higher rates at bay sites ($p=0.02$) where hydrologic connectivity is high and sediment resuspension more intense. Sites with high connectivity had significantly higher rates of carbon accumulation (averaging 376 ± 50 g C m^{-1} yr^{-1}) compared to sites with moderate or low connectivity. We also found high rates of carbon accumulation in brackish sites where connectivity was low and biomass production was characteristically higher than in saline sites. A stepwise regression model explained 81% of variability in carbon accumulation rates across all sites. Our data indicate deltaic wetlands can be important sinks for blue carbon, contributing to climate change mitigation.

1.! Introduction

Delta landscapes are a heterogeneous mix of diverse wetland habitats across a range of salinities. Their location at the mouths of rivers creates a substantial interface with adjacent terrestrial, riverine, and marine zones, which contributes to high biodiversity and the provision of essential ecosystem services. This includes storm protection, habitat and nursery grounds for a variety of species, and water quality improvement through nutrient and pollutant removal (Mitra et al 2005, Ibáñez and Prat 2003, Macreadie et al. 2013). Deltas are also increasingly recognized for their ability to sequester and store large amounts of carbon, helping mitigate climate change (Pritchard 2009, Ibáñez et al. 2010, Callaway et al. 2012). Within delta wetlands, both sediment accretion and carbon accumulation rates show a high degree of spatial and temporal variability as a function of wetland type, their sources of water and sediment, elevation, and vegetation community composition and productivity (Chmura et al. 2003, Craft 2007). Despite their importance, deltas globally are threatened by human activities, most notably hydrologic alterations, sea-level rise (SLR) and subsidence (elevation loss) that is often exacerbated by reductions in sediment supply (Syvitski et al. 2009, Vorosmarty et al. 2009, Day et al. 2016). Other stressors can be severe, including nutrient enrichment, pollutant loading, and land use change, both locally and within the watershed (Giosan et al. 2014).

Deltas are sustained where rivers discharge enough sediment to counter SLR and local subsidence rates. The delivery of both sediment and sediment-bound carbon leads to the vertical accretion of marsh surfaces, countering sediment compaction and subsidence that occurs deeper in the soil profile (Morris et al. 2002, Chmura 2009, Webb et al. 2013). Over the past century, sediment transport in rivers worldwide has declined markedly, for example in the Mississippi where sediment loads have decreased by 69% since it was first dammed, and in Mediterranean

Rivers, for example the Rhone and Ebro, where sediment loads have been reduced by as much as 85-95% (Giosan et al. 2014, Day et al. 2014, Rovira et al. 2015). While some river systems like the Rhone still have large floods that carry substantial sediment loads (Pont et al. 2017), the overall reduction in riverine sediment inputs contributes to lower vertical accretion rates that can lead to decreasing land elevation and an increased risk of saltwater intrusion and flooding (Syvitski et al. 2009, Genua-Olmedo et al. 2016). Over the next century, increasing rates of SLR are expected to raise sea levels by as much as a meter (IPCC 2013), exacerbating conditions in delta regions that are already undergoing land subsidence. If deltas are to persist, vertical accretion must keep pace with SLR; accretion depends in part on the ecological condition of delta wetlands and the eco-geomorphic feed-backs between vegetation and accretion rates (Morris et al. 2002, Ibáñez et al. 2014).

One effect of sediment accretion is the accumulation of sediment-bound carbon (allochthonous carbon) that is delivered and deposited on wetland surfaces (Macdonald et al. 1998, Ibáñez et al. 2010). This is coupled with carbon fixation in aboveground and belowground biomass (autochthonous carbon) that can be permanently buried in sediments, making coastal and deltaic wetlands natural carbon sinks (Craft 2007, Callaway et al. 2012). In spite of their small area globally, they hold a disproportionate amount of the earth’s total soil carbon, helping to regulate climate change through carbon uptake and long-term storage (Bridgham et al. 2006, Chmura 2009, Mitsch et al. 2013). Until relatively recently, research on the ability of ecosystems to sequester carbon has focused on terrestrial (primarily tropical) forests, but the quantity of carbon sequestration and storage by coastal ecosystems, the so-called “blue-carbon,” is an important component of the global carbon cycle. Annually, the global rate of carbon burial for salt marshes (87 ± 10 Tg C yr^{-1}) is estimated to exceed that of tropical rainforests (53 ± 10 Tg C yr^{-1}), which have long been considered the most significant global terrestrial carbon sink (Mcleod et al. 2011). Through these processes carbon can be held in biomass over annual to decadal time scales, and in sediments over much longer (perhaps millennial) scales (Macreadie et al. 2013). The on-going accumulation of sediment and carbon in a rising sea level scenario leads to the vertical accretion of marsh surfaces, increasing surface elevation, and carbon can accumulate almost indefinitely under these circumstances (Morris et al. 2002, Chmura 2009, Webb et al. 2013). In the microtidal Mediterranean, sediment delivery mostly occurs episodically via freshwater flows during periodic river flooding and salt water flows during marine storm events, rather than through daily tidal inundation (Pont et al. 2017). The input of freshwater and the associated nutrients also lead to increased primary productivity, helping build soil organic matter (Hensel et al. 1999, Craft 2007, Day et al. 2011, Calvo-Cubero et al. 2013).

Despite the recognition that delta ecosystems are important carbon sinks, there are gaps in our understanding of sediment and carbon dynamics in deltaic systems (Bianchi and Allison 2009, Webb et al. 2013). For instance, upstream hydrologic disturbance due to water management schemes (i.e., dams, irrigation, etc.) or land use change can reduce carbon accumulation rates and release buried sediment carbon as a result of erosion, leaching, and microbial mineralization (Ibánez et al. 2010, Macreadie et al. 2013). Further complicating this are differences in carbon burial rates that might arise as a function of variable habitat conditions and intensity of human alteration within regional wetland complexes. Deltaic wetlands are typically a mix of habitat types that vary in salinity, geomorphic position, hydroperiod, and vegetation type, all of which exert some control on the patterns of sediment and carbon accumulation (Hensel et al. 1999, Ibáñez et al. 2010, Day et al. 2011).

Few studies, especially in the Mediterranean have investigated the environmental factors that control spatially variable sediment and carbon accretion rates, and the resulting elevation changes across large regional wetland complexes (Day et al. 2011). Earlier work in the Ebro Delta focused on sediment accretion, and showed that accretion rates were highest in hydrologically connected marshes at 0.5 cm yr^{-1} (with corresponding vertical elevation increases of 0.66 cm yr^{-1}); rates were lowest in sites lacking river connections (0.14 cm yr^{-1}) with corresponding surface elevation increases of 0.09 cm yr^{-1} (Ibañez et al. 1997, 2010). These studies were not designed to quantify the contribution of carbon accumulation rates, which are also expected to vary widely as a function of plant species composition, salinity, water level, human disturbance, and the influx of water and sediments from river flooding or storm events (Craft 2007, McLeod et al. 2011). Salinity is a particularly important variable because of its negative influence on plant community biomass production (Curcó et al. 2001), which in turn can alter the ecosystem services related to carbon sequestration and storage. For instance, Craft et al. (2009) found that the ecosystem services associated with biomass production were higher in brackish compared to salt marshes, where primary production is typically higher. Similar research on the sequestration of blue carbon in wetlands of the Mediterranean region is lacking.

Here we investigate factors that affect sediment and carbon accumulation rates, and the resulting change in surface elevation in the Ebro River Delta. We measured sediment accretion rates using three different dating methods; short-term measurements at the soil surface (horizon markers) and longer- term measurements based on soil cores (^{137}Cs and ^{210}Pb dating), as well as soil carbon content and carbon accumulation rates in 15 delta marshes that vary in salinity, hydroperiod, geomorphological setting, elevation, plant community composition, and their relative degree of connectivity to other surface waters. We hypothesize that sites with greater hydrological connectivity and freshwater inputs will have higher sediment accretion and carbon accumulation rates, leading to more rapid surface elevation increases. Understanding what drives the dynamics of sediment and carbon accumulation, and assessing the ability of wetlands to build vertically and keep pace with SLR will aid in management activities that promote the resilience of delta wetlands. While previous studies have investigated this topic in constructed wetlands (Calvo-Cubero et al., 2013, 2014) and in other regions with a Mediterranean-climate (Callaway et al. 2012, Morris et al. 2013), this is the first study assessing carbon sequestration rates in coastal wetlands of the Mediterranean basin.

2.! Methods

The Ebro River Delta in Catalonia, Spain, covers 330 km^2, of which about 80 km^2 are brackish and saline natural wetlands (Figure 1). They provide some of the most important habitats for fish and waterfowl in the western Mediterranean, as well as other important ecosystem services such as storm protection, water quality benefits, and educational and recreational opportunities (Ibáñez et al. 1997). Much of the rest of the deltaic plain (65%) is in agricultural land use devoted to rice production. The delta is experiencing coastal retreat at the river mouth by wave action and subsidence because the influx of new sediments is not enough to counter these forces (Ibáñez et al. 2010). Like many deltas globally, marshes in the Ebro delta suffer from sediment starvation as a result of altered hydrology - primarily the construction of large numbers of dams within the watershed that act as sediment traps and have reduced the flow of sediment and organic matter from the Ebro River to the delta by an estimated 99% (Ibáñez and Prat 2003, Rovira et al. 2015).

Fifteen sites in the Ebro River delta were selected for this study (Table 1), including nine brackish marshes and six salt marshes that vary in their landscape or geomorphological position, and the degree of connection to other surface waters. The sites are marshes located at the mouth of the Ebro river, adjacent to coastal lagoons and Mediterranean bays, and impoundments within the delta. The delta has a long history of anthropogenic disturbance including salt production, grazing, small urban settlements and the widespread conversion of marshes to rice fields that are fed by a network of irrigation canals. This represents widespread hydrologic alteration that has affected the degree to which wetlands are connected to sources of freshwater (river) and saltwater (sea). At present only about 25% of the Ebro River delta is natural habitat (Benito et al. 2014).

With the exception of the Garxal marshes located at the mouth of the Ebro River, the wetlands are isolated from direct river flooding and have limited input of freshwater and river sediments (e.g., there is a small input through the irrigation or drainage networks). The coastal lagoon and bay wetlands have some degree of connection, for instance the Encanyssada lagoon marshes have a limited connection to the Ebro delta bays and are dominated by plant species such as and . Three salt marsh sites are located on the large Alfacs and Fangar bays that have formed as a result of long-term sediment transport from the Delta's coastline and are hydrologically open to exchange with the open water of the bays. Two types of impounded wetlands are also found: marshes impounded by human activity (isolated by canals, abandoned rice fields, etc.) and naturally impounded fresh to brackish high organic soil marshes fed primarily by groundwater inflows. These are naturally disconnected from other surface waters.

As a result of this heterogeneous landscape, the wetlands in this study can be arranged along a continuum of hydrologic connectivity between each site and any adjacent surface waters. We placed them into three categories (high, moderate, and low) of relative hydrologic connectivity using hydrological records, mapping of the delta, and our long history of site visits and knowledge of the sites (Ibañez et al. 2010):

- High: direct hydrologic connection with open exchange between the wetland and the Ebro River and/or the Mediterranean Sea.
- Moderate: periodic hydrologic connections between the wetland and adjacent water bodies (e.g., lagoons) in periods of high water levels or storms.
- Low/None: wetlands are rarely or never connected to adjacent waters due to impoundments.

While the result is a qualitative ranking, it provides an indication of differences in site hydrology (Table 1).

Marker horizons and Surface Elevation Tables (SETs) were used to measure short-term rates of vertical accretion and any change in the surface elevation of the wetlands, respectively (Cahoon and Turner 1989, Callaway et al. 2013). Replicate plots (n=2) were established in each site in 2009 in a representative 50x50 m area of the marsh. Each plot was 4x4 m in size with a SET station in the center, and three randomly placed 1-m^2 marker horizons within the plot. The marker horizons consisted of a layer of kaolinite placed on the marsh surface. SET measurements were made quarterly between September 2009 and September 2012. Marker horizons were sampled in 2013, giving incubation times of 46 or 47 months.

The SET data were used to calculate marsh surface elevation at each site by taking the average of each of the four fixed positions (9 readings per position). The mean of the fixed positions was then averaged to obtain one elevation value for the location of each SET at each survey. Elevation change was calculated using linear regression of measurements from the initial readings at the time of SET installation across the time series to generate a linear rate of change (Callaway et al. 2013). The rates for each plot (n=2) were averaged for an overall rate for the site.

Estimates of sediment accretion rates were made by gamma analysis of ^{137}Cs and ^{210}Pb soil cores collected at each site. Soil cores were collected to a depth of 48 cm using a cylindrical PVC corer sealed with a screw top and an interior diameter of 11.5 cm. Each core was sectioned into 4-cm increments (this thickness was used due to sampling constraints), dried to a constant weight at 60 ^{o}C, and weighed to determine bulk density. Samples were passed through a 2-mm diameter mesh sieve before determining particle size distribution by sieving for sand (2.0 – 0.5 mm diameter), silt (diameter < 0.5 mm and > 0.002 mm), and clay (diameter < 0.002 mm). The total carbon (%TC) and nitrogen content (%TN) of the soils was determined using a Carlo Erba NA 1500 analyzer. Because soils were not tested for carbonates prior to analysis, we present results as total soil carbon. Organic matter content was determined by loss on ignition (LOI; Craft et al. 1991).

Each 4-cm depth increment was analyzed for ^{137}Cs and ^{210}Pb. Cesium-137 was produced by aboveground thermonuclear testing that began in 1954, with peak fallout rates in 1964. With a half-life of 30 years, it is commonly used as a marker in soils where the peak ^{137}Cs activity in the soil profile corresponds to the soil surface in 1964. Sediment or organic matter above that depth in the soil profile is assumed to have accumulated since that time, providing a measure of vertical accretion rates (Ritchie and McHenry 1990). ^{210}Pb is a naturally occurring radionuclide with a half-life of 22.3 years that is used to estimate sediment accretion rates over the past 100-150 years (Craft and Richardson 1998). In this case, vertical accretion rates are calculated based on the distribution of excess ^{210}Pb with depth using the constant initial concentration model (e.g., Schelske et al. 1994). Samples were counted for 20 to 90 h by the CRII-RAD Laboratory (Valence, France) using an EGG/ ORTEC Type GMX (gamma hyperpure germanium N-type) detector.

^{210}Pb accretion rates were calculated by regressing the natural log of the ^{210}Pb activity with depth. The slope of the line (S) is equivalent to the activity of ^{210}Pb over the depth profile. Accretion rates (AR) are then calculated as:

$$AR = -\mathrm{Ln}2 \div 22.3 * 1 \div S$$

Carbon accumulation rates were calculated based on the ^{137}Cs peak using the formula:

C accumulation rate = SAR * BD * %TC
Where: SAR = sediment accretion rate derived from ^{137}Cs soil profile
BD = mean bulk density above the ^{137}Cs peak
%TC = mean % total carbon above the ^{137}Cs peak

Water levels were measured at each site (above or belowground relative to the soil surface) using OTT groundwater monitoring wells installed in each site (one well in the middle of two paired SET sites). At each site visit water samples were analyzed for temperature (T), salinity (ppt), conductivity (S cm^{-1}), dissolved oxygen (DO, mg L^{-1}) and pH using an YSI 556MPS

Multiprobe system. Data were collected monthly at all sites between August 2009 and January 2012.

Differences between site means were determined using ANOVA and the Tukey-Kramer HSD means comparison test. To investigate the influence of the measured environmental factors on rates of carbon accumulation, sediment accretion and elevation change, a stepwise regression model was used to select the best-fit model based on minimum Akaike Information Criterion (AIC) values. Predictor variables included site type and dominant vegetation, the water quality parameters salinity and DO, water levels, elevation, and sediment particle size distribution. Coefficients of variation (CV) for the water quality and water level data were calculated as the ratio of the standard deviation to the mean and used in the analysis as predictor variables. All statistical analysis was done using JMP v12.0.

3.! Results

Water quality and soil characteristics varied in the delta marshes as a function of geomorphological setting (Table 2), although differences were significant only for the CV of salinity ($p < 0.05$) and marginally significant for the CV of water levels ($p = 0.055$). Natural impoundments had the lowest mean water levels, while the bays, which are more open to hydrologic fluxes, had significantly higher variability in water levels, indicating more pulsing events (CV = 55.8, compared to 7.1 and 1.5 for lagoons and human impounded sites, respectively).

Soil total carbon (TC) content varied widely, from a mean low of 2.6% in a coastal lagoon site, to 36.4% in the river mouth site. The natural impoundments with their inflows of fresh groundwater had the highest mean soil TC at 19.7 ± 10.1%. Lagoon sites had the lowest mean TC (10.1 ± 8.8%) and also had the largest proportion of sand in their sediments (with a mean of nearly 65%).

We found clear ^{137}Cs peaks in the soil profile at all sites (see Figure 2 for examples of ^{137}Cs and ^{210}Pb soil profiles), and were able to date 10 of the 15 cores using ^{210}Pb. The ^{137}Cs maxima ranged from very near the soil surface (6 cm depth, for example at Tancada) to nearly the bottom of the core (38 cm at Alfacada), resulting in estimates of sediment accretion rates between 0.13 and 0.93 cm yr^{-1} (Table 3). Accretion rates measured using ^{137}Cs were slighter higher than rates measured using ^{210}Pb, which ranged from 0.11 to 0.84 cm yr^{-1}; there was also a fair amount of consistency between the accretion rates obtained at the individual sites by ^{137}Cs and ^{210}Pb, with a correlation coefficient of 0.69 for the two measures. Although there were differences in mean accretion rates when sites are grouped by geomorphological setting, differences were not significant (Figure 3). The Bay sites, located at the margins of the delta where wind is likely to resuspend and deliver sediment had the highest mean sediment accretion rates. Rates were lowest at an impounded site, Olles salt marsh, for both measures (0.13 and 0.11, for rates based on ^{137}Cs and ^{210}Pb, respectively); while the highest ^{137}Cs-values occurred at Fangar (a bay site, 0.84 cm yr^{-1}), and Alfacada and Encanyssada West (lagoons, 0.93 and 0.80 cm yr^{-1} respectively).

Short-term sediment accretion estimates based on horizon marker data were similar to the ^{137}Cs measurements, varying between 0.05 and 0.90 cm yr^{-1}, and again the highest and most consistent rates were seen in the bays (0.68 ± 0.34 cm yr^{-1}; Table 3). Surface elevations increased at all sites, at rates between 0.10 to 2.13 cm yr^{-1}. Overall, sediment accretion rates (both short and long-term measures) and elevation changes were lowest in the lagoons. Surface elevation increases were highest in the natural impoundments, averaging 1.96 ± 0.25 cm yr^{-1} ($p=0.02$), with the greatest increase in vertical elevation (2.13 cm yr^{-1}) at Ullals, a natural impoundment dominated by . In nearly all cases the surface elevation increases are higher than estimated rates of relative sea level rise in the delta of 0.5-0.7 cm yr^{-1} (Prado et al. 2019).

Rates of carbon sequestration based on ^{137}Cs dating were also highly spatially variable, ranging from 32 to 435 g C m^{-1} yr^{-1} (Table 3). As with sediment accretion rates, bays had the highest mean rate at 367 ± 84 g C m^{-1} yr^{-1}, fully three times higher than in the lagoons, which had the lowest rate (110 ± 90 g C m^{-1} yr^{-1}). Contrary to our initial hypothesis, some of the highest rates of carbon burial were seen in salt marshes, including Punta Banya located on the Alfacs Bay, at 435 g C m^{-1} yr^{-1}. The lowest rates were recorded in a brackish marsh located adjacent to a coastal lagoon (Encanyssada East, 32 g C m^{-1} yr^{-1}) and a salt marsh with low biomass located in the backshore of a beach (Buda Platja, 39 g C m^{-1} yr^{-1}). The River Mouth site (Garxal), which is hydrologically connected to the Ebro and its sediment and nutrient loads, was among the highest at 324 g C m^{-1} yr^{-1}. Overall, mean TC accumulation rates in brackish and salt marshes were nearly identical, at 204 and 207 g C m^{-1} yr^{-1}. Our data show that sites with a high degree of hydrologic connectivity had significantly higher rates of carbon accumulation averaging 356 ± 50 g C m^{-1} yr^{-1} compared to 123 ± 58 and 166 ± 44 g C m^{-1} yr^{-1} in the sites ranked with moderate and low connectivity ($p= 0.013$; Figure 4). The relatively high mean carbon accumulation rates at the impounded sites (low connectivity, Table 3) may be related to high rates of primary productivity, particularly in the three brackish sites where the highly productive species or dominate the plant community (Ibañez et al. 2010). In the impounded salt marsh site dominated by (Olles Impounded), carbon accumulation was low (53 g C m^{-1} yr^{-1}). Thus, we found the highest carbon accumulation rates under two conditions that appear to differ in their primary sources of carbon. The first is where hydrological connectivity to other surface waters is relatively high, allowing inputs of allochthonous carbon, and the second is where connectivity is low, yet biomass production is high under brackish conditions allowing inputs of autochthonous carbon. This lends support to our hypothesis that sites with greater hydrologic connectivity support higher carbon accumulation rates. Carbon fixation in biomass and its subsequent incorporation into soils at sites where connectivity is low is another mechanism for high rates of carbon accumulation.

Stepwise regression analysis indicates that the geomorphologic setting, water level fluctuations (water level CV), salinity, and sediment particle size were important in explaining variability in sediment accretion, carbon accumulation, and surface elevation change across sites (Table 4). Short term sediment accretion as measured by horizon markers varied with geomorphological setting and was higher where water level variability (hydrologic pulsing) was high; the model explained 82% of the variation in the short-term accretion rates ($p = 0.003$). Increases in surface elevation were positively related to elevation and directly to carbon accumulation rates ($R^2 = 0.75$, $p= 0.001$; Table 4), demonstrating the role of organic matter in building soils. Increases in surface elevation were greatest at the natural impoundments, which occur in the interior of the delta (away from shorelines) where elevations are high (Vilacoto at

1.78 cm-yr^{-1} and Ullals at 2.13 cm yr^{-1}). These sites have soils that are high in carbon (mean TC 19.7 ± 10.1%) and vegetation is dominated by the highly productive species . Carbon accumulation rates were negatively related to both mean salinity and its variability, where lower salinity was associated with higher rates of carbon accumulation (R^2 = 0.81, p= 0.02). Like sediment accretion, carbon accumulation rates tend to increase as water levels become more variable, although the effect of water level variability was small.

4.! Discussion

Rates of carbon and sediment accumulation, and surface vertical elevation change varied across the Ebro River Delta in response to the environmental variables of landscape position (geomorphological setting), salinity, and water level fluctuations. Vertical accretion rates were higher at sites where high hydrologic connectivity can cause surface water pulsing events as a function of winds, overwash inputs during storms, and riverine inputs during high flows (e.g., to the river mouth and bay sites; Day et al. 1995, 2011). Carbon accumulation and vertical accretion rates were also high in the brackish, impounded sites, which support highly productive plant species such as that add autochtonous carbon to build marsh soils (Windham 2001, Moore et al. 2012). Nutrients carried by the Ebro river may contribute to high organic matter production at the river mouth site, although there are indications that nutrient concentrations have decreased over the past several decades. For example, Ibañez et al. (2011) report that soluble reactive phosphorus declined from a mean annual maximum of 294.9 µg l^{-1} in 1990 to a low of 43.8 µg l^{-1} in 2005. Nitrate also varied from a maximum of 2.9 mg l^{-1} in 1992 to a low of 2.0 mg l^{-1} in 2003. Drainage from rice fields also creates a subsidy for plant growth, for example Calvo-Cubero et al. (2013) found phosphate levels of 0.13 mg L^{-1} and total nitrogen concentrations of 1.1 mg L^{-1} in agricultural drainage water in the Ebro Delta.

Overall, carbon accumulation rates in the delta marshes ranged from 32 to 435 g C m^{-2} yr^{-1}, reflecting the high spatial variability common to estimates of carbon burial in coastal systems (Mcleod et al. 2011, Ouyang and Lee 2014). Consistent with sediment accretion, carbon sequestration rates were significantly higher in the bays where water levels fluctuate widely and the wetlands experience more wind driven water and sediment movement (Perez et al. 2000, Ibañez et al. 2010). Wind driven sediment movement can be substantial, for instance Booth et al. (2000) found in a modeling study of microtidal bays in coastal Louisiana, that wind speeds of 4 m s^{-1} were high enough to resuspend approximately 50% of bottom sediments on an aerial basis. Generally, the concentration of suspended sediments is correlated with high wind events that resuspend and move bottom sediments (Perez et al. 2000). As in many coastal ecosystems, carbon accumulation in the Ebro Delta wetlands is due to both external (allochthonous) and internal (autochthonous) inputs: external sources include organically enriched fine sediments of the bay and the transport of the products of macrophyte breakdown (rice plants and seagrasses), while internal sources result from algae and plant (both aboveground and belowground) biomass production (e.g., Windham 2000, Ibáñez et al. 2002, Calvo-Cubero et al. 2013). The fine sediment rich in organic matter and nutrients originates in the rice fields and is transported through the drainage network into the bay where it is re-suspended and redistributed by winds (Ibañez et al. 2002). This helps explain why Punta Banya, a salt marsh located at the margin of Alfacs bay and exposed to dominant winds, had the highest rate of carbon sequestration recorded in this study (435 g C m^{-2} yr^{-1}; Table 3). This site sits at the lowest elevation of any of the sites, with variable water levels and a high proportion of sand in the soil profile (Table 2) due to deposition from the lateral movement of sediment along the sand barrier that defines the bay. The relatively dense sandy soils (BD of 1.15 g cm^{-3}) and high organic carbon content combine to give this site high carbon sequestration rates.

Conditions at the Garxal river mouth sites lead to high carbon accumulation as a result of the subsidy of riverine sediment and nutrients from the Ebro River (Torrecilla et al. 2005); and marine inputs that occur during storm events. These sites also receive carbon and nutrient inputs from marsh plant decomposition and macrophyte litter from the Garxal lagoon (Ibañez et al. 2010). The site is brackish and dominated by and , and the organic carbon content of the surface soils are the highest we measured; 36% TC at the surface with correspondingly low bulk density (0.49 g cm^{-3}). The result is a high rate of carbon accumulation of 325 g C m^{-2} yr^{-1}. In contrast, sediment and carbon accumulation rates were over three times lower in the lagoons. Many of the lagoon sites, such as Tancada, have a restricted hydrologic connection with Alfacs Bay and the open sea, effectively limiting sediment movement and carbon accumulation. Limited hydrologic connectivity that results in reduced inputs of sediment and associated nutrients have been shown in many systems including coastal wetlands in Georgia (USA; Craft and Casey 2000), the Chesapeake Bay (USA; Noe and Hupp 2009), and the Peace–Athabasca Delta (Canada; Long and Pevelsky 2013).

At all sites, vertical accretion rates varied as a function of the temporal scale of the measurement; for example, in the lagoons, natural impoundments, and the river mouth sites, short-term sediment accretion rates (as measured by horizon markers) were significantly lower (with means of 0.24, 0.27, and 0.27 cm yr^{-1}) than the medium-term rates (circa 50 years) as measured by ^{137}Cs dating (0.47, 0.42, and 0.58 cm yr^{-1}). This temporal difference may be explained in part by dam construction on the Ebro River, for example the Mequinenza and

Ribarroja large dams, which were completed in 1965 and 1969, respectively. These have contributed to a substantial reduction in riverine sediment loads in the last half century leading to reduced sediment transport from the River to the Delta marshes (Ibáñez et al. 1997, Rovira et al. 2015).

The biggest gains in surface elevation were found at the natural impoundments that are isolated from surface water inflows (Ullals, Vilacoto) and the river mouth sites (Garxal) at 2.13, 1.78, and 1.05 cm yr^{-1}, respectively. These sites have low salinities and relatively high soil carbon, conditions that contribute to soil building. At these sites, short term sediment accretion rates above the markers were much lower. For example, at the Ullals site horizon markers showed an increase of 0.25 cm yr^{-1} while surface elevation increased by 2.13 cm yr^{-1} and carbon accumulation by 217 g C m^{-2} yr^{-1}. This is related to the dense growth of which has high rates of belowground biomass production, reported to vary, for example, between 640 and 6,250 g m^{-2} in coastal marshes on the US Atlantic coast (Moore et al. 2012). In the Ebro Delta marshes have been reported to produce belowground biomass of 3,740 g m^{-2} and marshes as high as 8,070 g m^{-2} (Ibáñez et al. 2002); this high rate of biomass production leads to a rise in surface elevation. Both the estimates of ^{137}Cs sediment accretion and SET surface elevation change include the organic matter incorporated to the soil by root growth, however the surface horizon marker estimates, which measure above the root zone, do not (Turner et al. 2000, Baustian et al., 2012). For this reason, accretion rates from ^{137}Cs and ^{210}Pb were higher than accretion as measured by marker horizons.

Although salinity was a predictor of carbon accumulation rates (Table 4), we found no significant difference in carbon accumulation rates between brackish and salt marshes, reflecting the high variability in site conditions within each group. However, increases in surface elevation were twice as high in brackish compared to salt marsh sites (with means of 0.95 and 0.49 cm yr^{-1}, respectively), as were ^{137}Cs sediment accretion rates at 0.55 compared to 0.36 cm yr^{-1}. Callaway et al. (2012) also found no difference in carbon accumulation between brackish and salt marshes in a study of the Mediterranean-type wetlands in San Francisco Bay. However, many studies of coastal wetlands (e.g., Loomis and Craft 2010) report significantly higher rates of carbon accumulation under brackish conditions. Typically, the influx of fresh water with its associated nutrient loads into brackish sites favors the accumulation of organic matter from highly productive plant species such as Lane et al. (2017) found this when nutrient rich water in treated municipal effluent was added to forested wetlands in the Mississippi River delta, increasing carbon sequestration. However, in some cases this can be offset by higher rates of carbon remineralization in the presence of sulfate, an efficient terminal electron acceptor (Poffenbarger et al. 2011).

Carbon accretion rates in the delta marshes (32 to 435 g C m^{-2} yr^{-1}) are well within the range of carbon accumulation reported in other studies (Mcleod et al. 2011, Ouyang and Lee 2014). In a comprehensive review of tidal wetlands, Chmura et al. (2003) report a range of 18 – 1,713 g C m^{-2} yr^{-1} with a global average of 210 g C m^{-2} yr^{-1}; a more recent estimate gives a slightly higher value of 245 g C m^{-2} yr^{-1} (Ouyang and Lee 2014). These are close to the average of the sites sampled in this study (205 g C m^{-2} yr^{-1}). We found carbon accumulation rates differed by wetland class, however there was also high variability within all geomorphological groups due to other environmental factors. Quantifying the spatial variability in rates is a first step in mapping regional carbon sinks in order to plan conservation and restoration efforts, and more fully understand the mechanisms that control carbon sequestration (McLeod et al. 2011, Nahlik and Fennessy 2016).

5.! Conclusions

Our data support the hypothesis that sites with greater hydrological connectivity have higher carbon accumulation rates. This provides several insights related to the restoration and management of blue carbon stocks. One is that deltaic wetlands are effective carbon sinks, particularly where sites have been allowed to maintain their connectivity to other surface waters. Maintaining connectivity where it exists, and restoring it where possible, allows the transfer of sediment, carbon, nutrients and energy within a landscape (Turner et al, 2000, Pringle 2003, Syvitski et al. 2009) linking different habitats in the delta across a range of spatial and temporal scales, and promoting processes that sustain marsh surfaces and preserve soil carbon, including plant primary productivity. However, what is not known is whether this capacity of wetlands in the Mediterranean to act as sinks for carbon dioxide might be offset by methane production, which could lead to a net positive radiative forcing of climate (Neubauer and Megonigal 2015, Lane et al. 2016). The balance of carbon fluxes, including methane emissions, deserves more study to fully understand the carbon dynamics of these systems and the controls on carbon flux rates that determine their role as greenhouse gas sinks, especially at low salinity sites where methane flux rates tend to increase (Pendleton et al. 2012).

Secondly, these data help support the growing body of research showing a negative relationship between human disturbance (for instance in the Ebro delta as indicated by land use change and hydrologic alteration) and soil carbon sequestration and storage (McLeod et al. 2013, Macreadie et al. 2013, Nahlik and Fennessy 2016, Fennessy et al. 2018). Human disturbance and land conversion has been shown to increase carbon dioxide emissions from soils in coastal wetlands, equivalent to an estimated 0.15 to 1.02 Pg C globally (Pendleton et al. 2012). Human activities that uncouple hydrologic linkages such as in the Ebro Delta not only slow carbon sequestration rates, but may lead to a loss of ancient carbon stored deeper in the soil profile through increased rates of decomposition (Pendleton et al. 2012).

The ability to make sound management decisions that are linked to conservation and climate policies depends on understanding the interactions of hydrology, sediment movements, and carbon dynamics (Callaway et al. 2012, Temmerman et al. 2013, Web et al. 2013, Ibáñez et al. 2014). This is particularly urgent if policies designed to maintain or restore coastal wetlands for carbon storage are to be implemented. Identifying the characteristics of wetlands that rapidly sequester carbon can be used to help target wetlands or wetland types that provide this ecosystem service, providing an argument for their protection and restoration. Managing deltaic wetlands to maintain hydrologic connectivity is a key strategy to enhance their resilience in the face of environmental change.

Acknowledgments

This study was funded by the Government of Spain (Ministerio de Medio Ambiente, Research Project 056/RN08/04.3, Development of techniques to compensate subsidence and sea level rise in coasts and wetlands of the Ebro Delta, 2009–2010). Siobhan Fennessy was supported by a Fulbright Research Fellowship.

References

Benito, X., Trobajo, R. and Ibáñez, C. 2014. Modelling habitat distribution of Mediterranean coastal wetlands: The Ebro delta as case study. Wetlands 34:775–785.

Baustian, J. J., Mendelssohn, I. A. and Hester, M. W. 2012. Vegetation's importance in regulating surface elevation in a coastal salt marsh facing elevated rates of sea level rise. Glob Change Biol, 18: 3377–3382. doi:10.1111/j.1365-2486.2012.02792.

Bianchi, T. S., and Allison M.A. 2009. Large-river delta-front estuaries as natural "recorders" of global environmental change. Proceedings of the National Academy of Sciences of the United States of America 106:8085–92.

Booth, J.G., Miller, R.L., McKee, B.A., Leathers, R.A. 2000. Wind-induced bottom sediment resuspension in a microtidal coastal environment, Continental Shelf Research 20 (2000) 785}806

Bridgham, S. D., Megonigal, P. J., Keller, J. K., Bliss, N. B., & Trettin, C. 2006. The carbon balance of North American wetlands. Wetlands 26: 889-916.

Cahoon, D. R., & Turner, R. E. 1989. Accretion and canal impacts in a rapidly subsiding wetland II. Feldspar marker horizon technique. Estuaries and Coasts 12: 260-268.

Callaway, J. C., Borgnis, E. L., Turner, R. E., and Milan, C. S. 2012. Carbon Sequestration and

Baustian, J. J., Mendelssohn, I. A. and Hester, M. W. 2012. Vegetation's importance in regulating surface elevation in a coastal salt marsh facing elevated rates of sea level rise. Glob Change Biol, 18: 3377–3382. doi:10.1111/j.1365-2486.2012.02792.

Bianchi, T. S., and Allison M.A. 2009. Large-river delta-front estuaries as natural “recorders” of global environmental change. Proceedings of the National Academy of Sciences of the United States of America 106:8085–92.

Booth, J.G., Miller, R.L., McKee, B.A., Leathers, R.A. 2000. Wind-induced bottom sediment resuspension in a microtidal coastal environment, Continental Shelf Research 20 (2000) 785}806

Bridgham, S. D., Megonigal, P. J., Keller, J. K., Bliss, N. B., & Trettin, C. 2006. The carbon balance of North American wetlands. Wetlands 26: 889-916.

Cahoon, D. R., & Turner, R. E. 1989. Accretion and canal impacts in a rapidly subsiding wetland II. Feldspar marker horizon technique. Estuaries and Coasts 12: 260-268.

Callaway, J. C., Borgnis, E. L., Turner, R. E., and Milan, C. S. 2012. Carbon Sequestration and

Baustian, J. J., Mendelssohn, I. A. and Hester, M. W. 2012. Vegetation's importance in regulating surface elevation in a coastal salt marsh facing elevated rates of sea level rise. Glob Change Biol, 18: 3377–3382. doi:10.1111/j.1365-2486.2012.02792.

Bianchi, T. S., and Allison M.A. 2009. Large-river delta-front estuaries as natural "recorders" of global environmental change. Proceedings of the National Academy of Sciences of the United States of America 106:8085–92.

Booth, J.G., Miller, R.L., McKee, B.A., Leathers, R.A. 2000. Wind-induced bottom sediment resuspension in a microtidal coastal environment, Continental Shelf Research 20 (2000) 785}806

Bridgham, S. D., Megonigal, P. J., Keller, J. K., Bliss, N. B., & Trettin, C. 2006. The carbon balance of North American wetlands. Wetlands 26: 889-916.

Cahoon, D. R., & Turner, R. E. 1989. Accretion and canal impacts in a rapidly subsiding wetland II. Feldspar marker horizon technique. Estuaries and Coasts 12: 260-268.

Callaway, J. C., Borgnis, E. L., Turner, R. E., and Milan, C. S. 2012. Carbon Sequestration and

Baustian, J. J., Mendelssohn, I. A. and Hester, M. W. 2012. Vegetation's importance in regulating surface elevation in a coastal salt marsh facing elevated rates of sea level rise. Glob Change Biol, 18: 3377–3382. doi:10.1111/j.1365-2486.2012.02792.

Bianchi, T. S., and Allison M.A. 2009. Large-river delta-front estuaries as natural “recorders” of global environmental change. Proceedings of the National Academy of Sciences of the United States of America 106:8085–92.

Booth, J.G., Miller, R.L., McKee, B.A., Leathers, R.A. 2000. Wind-induced bottom sediment resuspension in a microtidal coastal environment, Continental Shelf Research 20 (2000) 785}806

Bridgham, S. D., Megonigal, P. J., Keller, J. K., Bliss, N. B., & Trettin, C. 2006. The carbon balance of North American wetlands. Wetlands 26: 889-916.

Cahoon, D. R., & Turner, R. E. 1989. Accretion and canal impacts in a rapidly subsiding wetland II. Feldspar marker horizon technique. Estuaries and Coasts 12: 260-268.

Callaway, J. C., Borgnis, E. L., Turner, R. E., and Milan, C. S. 2012. Carbon Sequestration and

Baustian, J. J., Mendelssohn, I. A. and Hester, M. W. 2012. Vegetation's importance in regulating surface elevation in a coastal salt marsh facing elevated rates of sea level rise. Glob Change Biol, 18: 3377–3382. doi:10.1111/j.1365-2486.2012.02792.

Bianchi, T. S., and Allison M.A. 2009. Large-river delta-front estuaries as natural "recorders" of global environmental change. Proceedings of the National Academy of Sciences of the United States of America 106:8085–92.

Booth, J.G., Miller, R.L., McKee, B.A., Leathers, R.A. 2000. Wind-induced bottom sediment resuspension in a microtidal coastal environment, Continental Shelf Research 20 (2000) 785}806

Bridgham, S. D., Megonigal, P. J., Keller, J. K., Bliss, N. B., & Trettin, C. 2006. The carbon balance of North American wetlands. Wetlands 26: 889-916.

Cahoon, D. R., & Turner, R. E. 1989. Accretion and canal impacts in a rapidly subsiding wetland II. Feldspar marker horizon technique. Estuaries and Coasts 12: 260-268.

Callaway, J. C., Borgnis, E. L., Turner, R. E., and Milan, C. S. 2012. Carbon Sequestration and

Baustian, J. J., Mendelssohn, I. A. and Hester, M. W. 2012. Vegetation's importance in regulating surface elevation in a coastal salt marsh facing elevated rates of sea level rise. Glob Change Biol, 18: 3377–3382. doi:10.1111/j.1365-2486.2012.02792.

Bianchi, T. S., and Allison M.A. 2009. Large-river delta-front estuaries as natural "recorders" of global environmental change. Proceedings of the National Academy of Sciences of the United States of America 106:8085–92.

Booth, J.G., Miller, R.L., McKee, B.A., Leathers, R.A. 2000. Wind-induced bottom sediment resuspension in a microtidal coastal environment, Continental Shelf Research 20 (2000) 785}806

Bridgham, S. D., Megonigal, P. J., Keller, J. K., Bliss, N. B., & Trettin, C. 2006. The carbon balance of North American wetlands. Wetlands 26: 889-916.

Cahoon, D. R., & Turner, R. E. 1989. Accretion and canal impacts in a rapidly subsiding wetland II. Feldspar marker horizon technique. Estuaries and Coasts 12: 260-268.

Callaway, J. C., Borgnis, E. L., Turner, R. E., and Milan, C. S. 2012. Carbon Sequestration and

Baustian, J. J., Mendelssohn, I. A. and Hester, M. W. 2012. Vegetation's importance in regulating surface elevation in a coastal salt marsh facing elevated rates of sea level rise. Glob Change Biol, 18: 3377–3382. doi:10.1111/j.1365-2486.2012.02792.

Bianchi, T. S., and Allison M.A. 2009. Large-river delta-front estuaries as natural "recorders" of global environmental change. Proceedings of the National Academy of Sciences of the United States of America 106:8085–92.

Booth, J.G., Miller, R.L., McKee, B.A., Leathers, R.A. 2000. Wind-induced bottom sediment resuspension in a microtidal coastal environment, Continental Shelf Research 20 (2000) 785}806

Bridgham, S. D., Megonigal, P. J., Keller, J. K., Bliss, N. B., & Trettin, C. 2006. The carbon balance of North American wetlands. Wetlands 26: 889-916.

Cahoon, D. R., & Turner, R. E. 1989. Accretion and canal impacts in a rapidly subsiding wetland II. Feldspar marker horizon technique. Estuaries and Coasts 12: 260-268.

Callaway, J. C., Borgnis, E. L., Turner, R. E., and Milan, C. S. 2012. Carbon Sequestration and

United States of America 106:8085-8092.

Booth, J.G., Miller, R.L., McKee, B.A., Leathers, R.A. 2000. Wind-induced bottom sediment resuspension in a microtidal coastal environment, Continental Shelf Research 20 (2000) 785}806

Bridgham, S. D., Megonigal, P. J., Keller, J. K., Bliss, N. B., & Trettin, C. 2006. The carbon balance of North American wetlands. Wetlands 26: 889-916.

Cahoon, D. R., & Turner, R. E. 1989. Accretion and canal impacts in a rapidly subsiding wetland II. Feldspar marker horizon technique. Estuaries and Coasts 12: 260-268.

Callaway, J. C., Borgnis, E. L., Turner, R. E., and Milan, C. S. 2012. Carbon Sequestration and

Baustian, J. J., Mendelssohn, I. A. and Hester, M. W. 2012. Vegetation's importance in regulating surface elevation in a coastal salt marsh facing elevated rates of sea level rise. Glob Change Biol, 18: 3377-3382. doi:10.1111/j.1365-2486.2012.02792.

Bianchi, T. S., and Allison M.A. 2009. Large-river delta-front estuaries as natural ÒrecordersÓ of global environmental change. Proceedings of the National Academy of Sciences of the United States of America 106:8085-8092.

Booth, J.G., Miller, R.L., McKee, B.A., Leathers, R.A. 2000. Wind-induced bottom-sediment resuspension in a microtidal coastal environment, Continental Shelf Research 20 (2000) 785}806

Bridgham, S. D., Megonigal, P. J., Keller, J. K., Bliss, N. B., & Trettin, C. 2006. The carbon balance of North American wetlands. Wetlands, 26: 889-916.

Cahoon, D. R., & Turner, R. E. 1989. Accretion and canal impacts in a rapidly subsiding wetland II. Feldspar marker horizon technique. Estuaries and Coasts, 12: 260-268.

Callaway, J. C., Borgnis, E. L., Turner, R. E., and Milan, C. S. 2012. Carbon Sequestration and

Baustian, J. J., Mendelssohn, I. A. and Hester, M. W. 2012. Vegetation's importance in regulating surface elevation in a coastal salt marsh facing elevated rates of sea level rise. Glob Change Biol, 18: 3377–3382. doi:10.1111/j.1365-2486.2012.02792.

Bianchi, T. S., and Allison M.A. 2009. Large-river delta-front estuaries as natural ÒrecordersÓ of global environmental change. Proceedings of the National Academy of Sciences of the United States of America 106:8085–8092.

Booth, J.G., Miller, R.L., McKee, B.A., Leathers, R.A. 2000. Wind-induced bottom sediment resuspension in a microtidal coastal environment, Continental Shelf Research 20 (2000) 785}806

Bridgham, S. D., Megonigal, P. J., Keller, J. K., Bliss, N. B., & Trettin, C. 2006. The carbon balance of North American wetlands. Wetlands 26: 889-916.

Cahoon, D. R., & Turner, R. E. 1989. Accretion and canal impacts in a rapidly subsiding wetland II. Feldspar marker horizon technique. Estuaries and Coasts 12: 260-268.

Callaway, J. C., Borgnis, E. L., Turner, R. E., and Milan, C. S. 2012. Carbon Sequestration and

Baustian, J. J., Mendelssohn, I. A. and Hester, M. W. 2012. Vegetation's importance in regulating surface elevation in a coastal salt marsh facing elevated rates of sea level rise. Glob Change Biol, 18: 3377–3382. doi:10.1111/j.1365-2486.2012.02792.

Bianchi, T. S., and Allison M.A. 2009. Large-river delta-front estuaries as natural ÒrecordersÓ of global environmental change. Proceedings of the National Academy of Sciences of the United States of America 106:8085–8092.

Booth, J.G., Miller, R.L., McKee, B.A., Leathers, R.A. 2000. Wind-induced bottom sediment resuspension in a microtidal coastal environment, Continental Shelf Research 20 (2000) 785}806

Bridgham, S. D., Megonigal, P. J., Keller, J. K., Bliss, N. B., & Trettin, C. 2006. The carbon balance of North American wetlands. Wetlands 26: 889-916.

Cahoon, D. R., & Turner, R. E. 1989. Accretion and canal impacts in a rapidly subsiding wetland II. Feldspar marker horizon technique. Estuaries and Coasts 12: 260-268.

Callaway, J. C., Borgnis, E. L., Turner, R. E., and Milan, C. S. 2012. Carbon Sequestration and

Baustian, J. J., Mendelssohn, I. A. and Hester, M. W. 2012. Vegetation's importance in regulating surface elevation in a coastal salt marsh facing elevated rates of sea level rise. Glob Change Biol, 18: 3377-3382. doi:10.1111/j.1365-2486.2012.02792.

Bianchi, T. S., and Allison M.A. 2009. Large-river delta-front estuaries as natural ÒrecordersÓ of global environmental change. Proceedings of the National Academy of Sciences of the United States of America 106:8085-8092.

Booth, J.G., Miller, R.L., McKee, B.A., Leathers, R.A. 2000. Wind-induced bottom-sediment resuspension in a microtidal coastal environment, Continental Shelf Research 20 (2000) 785}806

Bridgham, S. D., Megonigal, P. J., Keller, J. K., Bliss, N. B., & Trettin, C. 2006. The carbon balance of North American wetlands. Wetlands 26: 889-916.

Cahoon, D. R., & Turner, R. E. 1989. Accretion and canal impacts in a rapidly subsiding wetland II. Feldspar marker horizon technique. Estuaries and Coasts 12: 260-268.

Callaway, J. C., Borgnis, E. L., Turner, R. E., and Milan, C. S. 2012. Carbon Sequestration and

Baustian, J. J., Mendelssohn, I. A. and Hester, M. W. 2012. Vegetation's importance in regulating surface elevation in a coastal salt marsh facing elevated rates of sea level rise. Glob Change Biol, 18: 3377–3382. doi:10.1111/j.1365-2486.2012.02792.

Bianchi, T. S., and Allison M.A. 2009. Large-river delta-front estuaries as natural ÒrecordersÓ of global environmental change. Proceedings of the National Academy of Sciences of the United States of America 106:8085–8092.

Booth, J.G., Miller, R.L., McKee, B.A., Leathers, R.A. 2000. Wind-induced bottom-sediment resuspension in a microtidal coastal environment, Continental Shelf Research 20 (2000) 785}806

Bridgham, S. D., Megonigal, P. J., Keller, J. K., Bliss, N. B., & Trettin, C. 2006. The carbon balance of North American wetlands. Wetlands 26: 889-916.

Cahoon, D. R., & Turner, R. E. 1989. Accretion and canal impacts in a rapidly subsiding wetland II. Feldspar marker horizon technique. Estuaries and Coasts 12: 260-268.

Callaway, J. C., Borgnis, E. L., Turner, R. E., and Milan, C. S. 2012. Carbon Sequestration and

Baustian, J. J., Mendelssohn, I. A. and Hester, M. W. 2012. Vegetation's importance in regulating surface elevation in a coastal salt marsh facing elevated rates of sea level rise. Glob Change Biol, 18: 3377–3382. doi:10.1111/j.1365-2486.2012.02792.

Bianchi, T. S., and Allison M.A. 2009. Large-river delta-front estuaries as natural ÒrecordersÓ of global environmental change. Proceedings of the National Academy of Sciences of the United States of America 106:8085–8092.

Booth, J.G., Miller, R.L., McKee, B.A., Leathers, R.A. 2000. Wind-induced bottom sediment resuspension in a microtidal coastal environment, Continental Shelf Research 20 (2000) 785}806

Bridgham, S. D., Megonigal, P. J., Keller, J. K., Bliss, N. B., & Trettin, C. 2006. The carbon balance of North American wetlands. Wetlands 26: 889-916.