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A Record of Anthropogenic Effects on Sedimentation in the Manatee River, Florida

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Abstract: Increased sedimentation rates have been attributed to increased anthropogenic activity in watersheds throughout Florida and many parts of the world. The Manatee River, located on the west coast of Florida (USA), like many other coastal watersheds, has experienced depletion in natural resources, increased nutrient loading, and increased pollution. LARs (linear accumulation rates) from watersheds throughout Florida suggest that anthropogenic activity increased bulk sedimentation by as much as 4-fold. The objective of this study was to construct a record of sedimentation and improve upon previous studies by determining individual sedimentary constituent MARs (mass accumulation rates) based on short lived radioisotopes (^{210}Pb and ^{234}Th) to characterize changes in sedimentation attributed to increased anthropogenic development. This study constructed records of sedimentary accumulation rates to compare pre-development records to the past 100 years of anthropogenic development and identified specific changes in sedimentation attributed to anthropogenic activity. Anthropogenic development increased deposition of terrigenous material into the river from 2-fold to 10-fold (0.3-2.0 g/cm^2/yr) over three periods: (1) predevelopment period (1900-1941); (2) agricultural development period (1941-1970); (3) urban development period (1970-2010). The mobilization of this amount of terrigenous material has implications for effects on water quality and biological communities within the river.

Key words: Sedimentation, lead-210, cesium-137, man induced effects, Florida, Tampa Bay.

1. Introduction

Increased coastal sedimentation rates have been attributed to increased anthropogenic activity (land-use change) in watersheds throughout Florida and many parts of the world [1-12]. The objective of this study was to determine if the Manatee River, located on the west-central Florida coast, was affected by such trends of increased sedimentation caused by anthropogenic activity, and to better characterize the sedimentary signal of that activity using MARs (mass accumulation rates) (as opposed to LARs (linear accumulation rates)) of individual sedimentary constituents.

This study examined records of sediment deposition during the anthropogenic development period (last 100 years). Changes in the types and amounts of sediment being introduced to the Manatee River, Tampa Bay, and ultimately the Gulf of Mexico were examined to determine the signature of anthropogenic land-use change. This study was the first to use MARs of specific constituents in the sediment to determine the effect of anthropogenic development on the fluvial and estuarine environments of the Manatee River.

1.1 Setting

The Manatee River is located on the west coast of Florida in the southeastern portion of the Tampa Bay Estuary (Fig. 1). The Manatee River Watershed has experienced increasing anthropogenic development (industrial, residential, and agricultural) over the last 100 years and was relatively pristine previous to this development. The population within the watershed has

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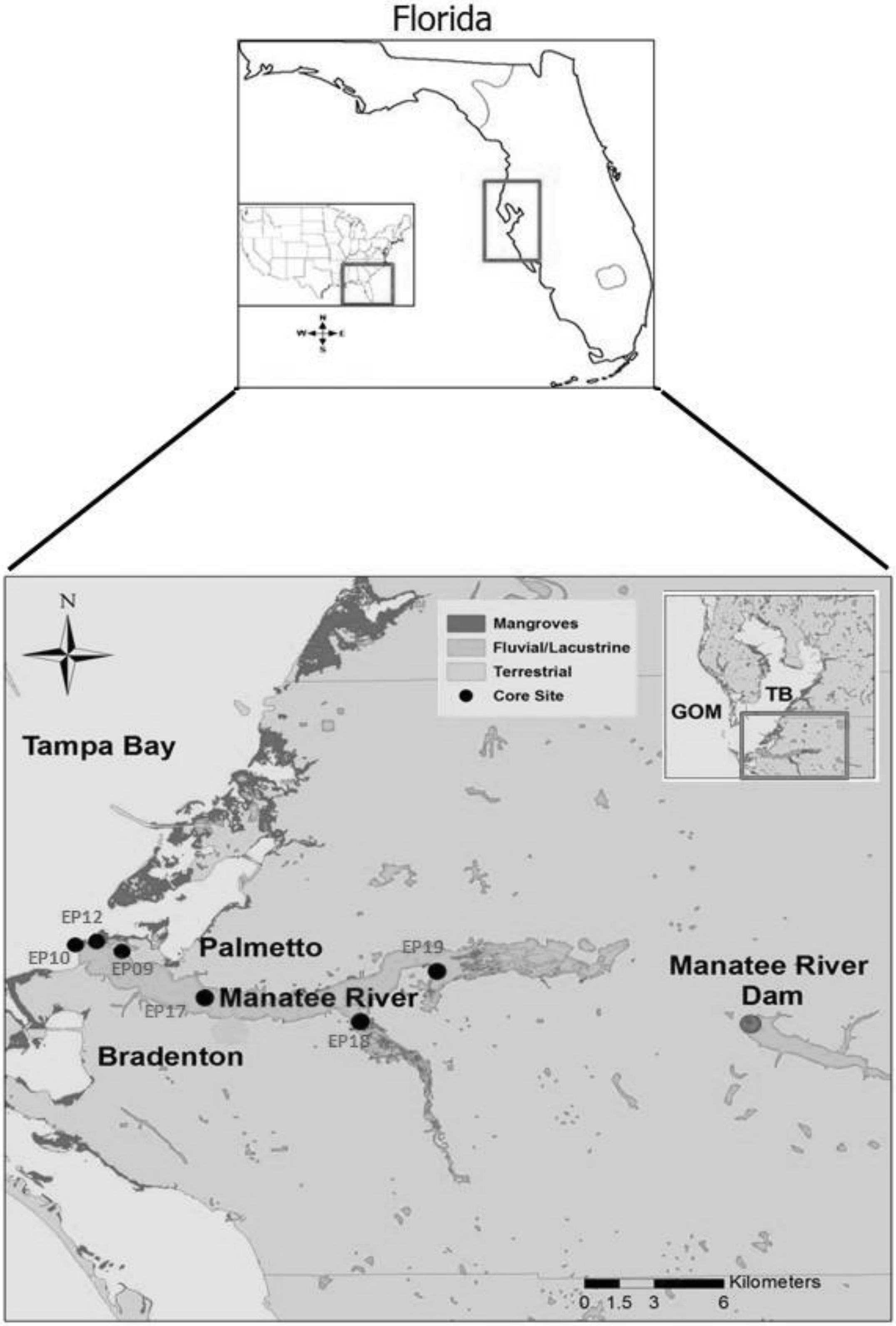

Fig. 1 Location map of Florida expanding to the location of the selected coring sites throughout the Manatee River with reference to the cities of Bradenton and Palmetto as well as the Manatee River Dam.

Table 1 Manatee County population estimates and projections from 1980-2020 (South Florida Water Management District, 2001).

Area	1980	1990	1995	2000	2010	2020
Manatee County	148,800	211,700	223,500	258,410	302,710	344,000
City of Bradenton	30,288	43,779	47,679	52,752	61,549	N/A
City of Palmetto	8,637	9,268	10,454	12,130	14,588	15,553

N/A means no projections were available.

doubled in the last 30 years (Table 1). The heavy residential development has led to depletion in natural resources, increased nutrient loading, coastal erosion, and increased pollution [13].

The Tampa Bay area is located on the west-central portion of the Florida coastline and totals approximately 7,000 km^2 including estuarine waters, wetlands and drainage basins. The bay is shallow with an average depth of 3.5 m and vegetation is dominated by mangrove forest with some areas of salt marsh, both of which contribute a significant portion of the organic matter in Tampa Bay sediment [14]. The Manatee River begins in Manatee County, FL, southeast of Tampa Bay at an elevation of 39.6 m and proceeds westward for 72.4 km. The river drains approximately 932.4 km^2 of land into the southern region of Tampa Bay and ultimately into the Gulf of Mexico [15].

There are two major sources of sedimentary input into the bay, marine sediments ($CaCO_3$) carried by tidal currents from the Gulf of Mexico and terrigenous sediments (fine-medium grain quartz sand) via fluvial systems [14, 16-17].

1.2 Sediment Accumulation Rates in Florida

Short-lived radioisotopes such as ^{137}Cs (cesium-137) and ^{210}Pb (lead-210) have been used for many applications to produce corroborating geochronologies for the past 100 years [1, 3-5, 7-9, 11].

^{210}Pb has been used in geochronological applications in both marine/coastal and lacustrine/watershed settings (Fig. 2). LARs (cm/year) have been found to be quite variable throughout Florida. Florida Bay had the highest accumulation rate of 0.33-5.8 cm/year [6]. The river-dominated areas (Steinhatchee, Charlotte Harbor, Saint Johns River Basin) had very similar linear accumulation rates with 0.14, 0.25-0.28, and 0.33 cm/year, respectively [2, 5, 10]. Brenner et al. [5] found that the sedimentation rate increased between 1.7-3.4-fold in the SJRB (Saint Johns River Basin) between pre-anthropogenic and anthropogenic times with an average of 0.33 cm/year. These changes were attributed to modifications in the hydrology of the fluvial system.

The sedimentation rate in Lake Okeechobee was intermediate at 0.78 cm/year and the lowest accumulation rate was reported in Rookery Bay at 0.14-0.17 cm/year [18-19]. Across a suite of cores in Lake Okeechobee, Brezonik and Engstrom [19] calculated that there had been a 2-fold increase in mass sediment accumulation rate (MAR, 3-6 g/cm^2/year) and a 4-fold increase in the rate of total phosphorus deposition in Lake Okeechobee since the early 1900s.

2. Methods

2.1 Sampling Methods

Six sediment cores were collected in the Manatee River (Fig. 1). The core sites were selected by locating areas with little potential for resuspension (low energy/basins) and as fine-grained as possible. The cores were collected by a diver-assisted push-coring method with 10 cm diameter acrylic barrel. Push cores provide a short-term environmental development record (hundreds of years before present). Sub-samples of each core were taken on a calibrated, threaded rod extrusion device. The sediment was extruded at 0.5 cm (0-10 cm) and at 1.0 cm for the remainder of each core.

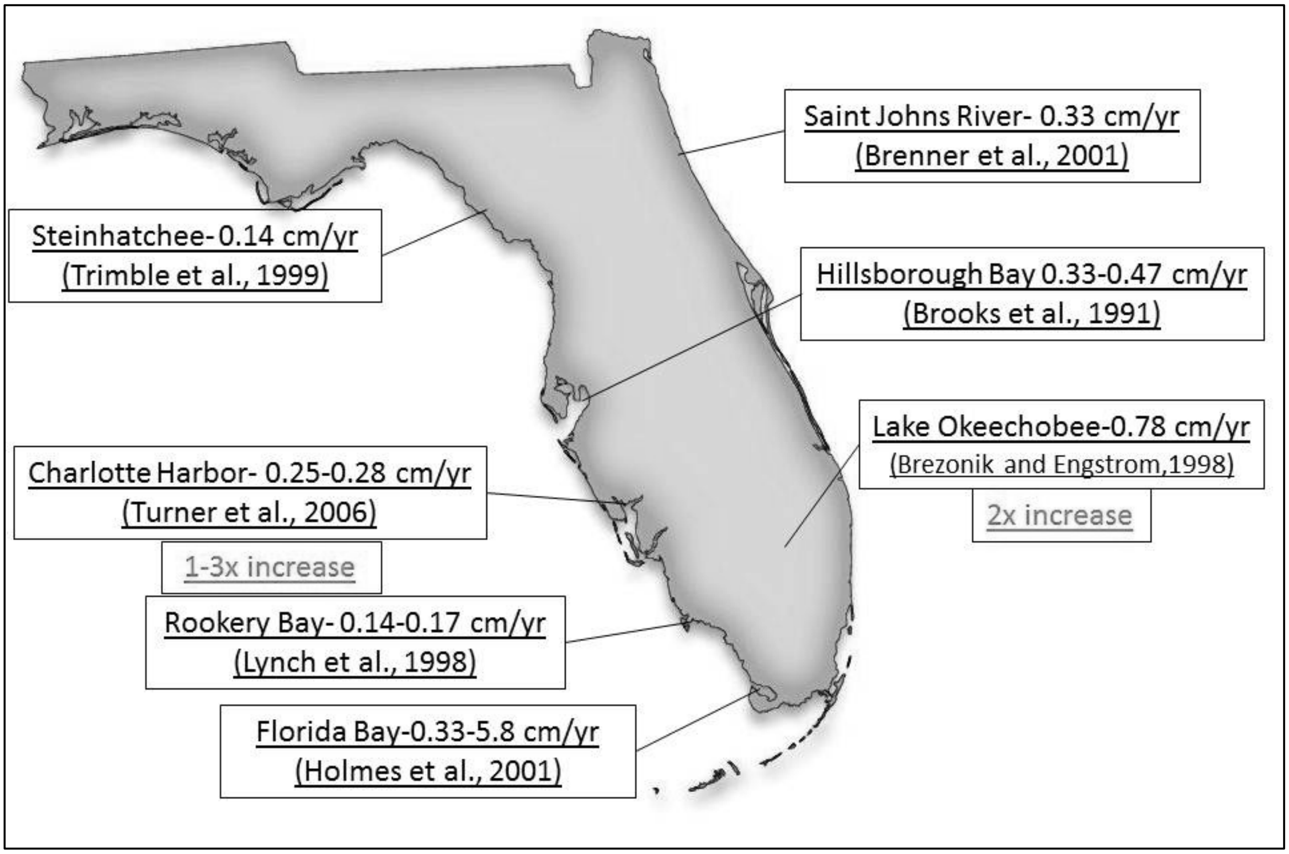

Fig. 2 A map of Florida depicting previous studies that have utilized LARs to determine anthropogenic change.

Samples were archived in plastic bags and frozen. The frozen samples were then freeze dried.

2.2 Sedimentology Laboratory Methods

Approximately 5 g of each sediment sample were sieved at 63 µm. Silt and clay weight percentages (fine fraction) were determined by using a Saturn DigiSizer High Resolution Laser Particle Size Analyzer at College of Marine Science, USF (University of South Florida). A manual pipetting method developed by Folk [20] was also used on certain samples to determine any errors in the DigiSizer measurement. It is assumed that the coarse fraction (sand and gravel) weight percentage is the difference between the fine fraction and 100% and is therefore not reported.

LOI (loss on ignition) analysis was used to determine the total organic matter and percent of carbonate material [21-22]. Approximately 1 g of each sample was placed into a crucible and ignited at 550 °C in a muffle furnace for 4 h and the percent of TOM (total organic matter) was determined by the mass difference after ignition. The remainder was then placed back into the muffle furnace and ignited at 950 °C for 1.5 h and the percent of carbonate (CO_3) content was determined by mass difference [21].

2.3 Radioisotope Laboratory Methods

A Canberra planar HPGe (high purity germanium) detector was used to determine ^{210}Pb and ^{137}Cs activity throughout each core at College of Marine Science, USF. For planar gamma detection, samples were freeze-dried and placed in vacuum-sealed aluminum canisters. Once sealed, the samples were allowed to achieve secular equilibrium for 28 days. The samples were then counted for 24-48 h based on sample size. Reported error is the product of the net uncertainty from the detector.

3. Theory and Calculation

Activity values for ^{137}Cs (661 keV emission energy) were reported directly. Unsupported ^{210}Pb (46.5 keV) values were determined by subtracting the average activity of the reported ^{214}Bi (209 keV), ^{214}Pb (295 keV) and ^{214}Pb (351 keV) from the reported activity of ^{210}Pb. MARs [23] and the CRS (constant rate of supply) model as described in Refs. [24-26] were also used to quantify the changes in sedimentation over time. Activities are reported in disintegrations per minute per gram (dpm/g). LARs are reported in centimeters per year (cm/year), whereas MARs, which incorporate flux (accumulation) per unit area per time, are reported in gram per square centimeter per year (g/cm^2/year).

4. Results

The lithology, radioisotope, and MARs records of the push-cores collected from the Manatee River are described below (Table 2). Each represents a record from a different sampling location and sedimentological response to natural and anthropogenic events. Criteria for selecting coring sites included as fine-grained surface sediment possible for highest possible radioisotope activity and areas likely to have the least resuspension due to tidal or river energy.

4.1 Lithology

The base of EP-09 was sand with abundant small shell fragments. Moving upcore, there were fine sand layers at 20 cm and 12 cm (Fig. 3). A fining upward sequence (increasing clay) occurred from 10 cm to 4.5 cm. A sudden increase in grain size (sand) occurred at 4 cm and another, smaller fining upward sequence terminated at the top of the core (3.5 cm to 0).

EP-10 was primarily (> 95%) quartz sand throughout, with small increases in fine grains (silt) at 22, 16-14, and 8 cm and almost no clay-size particles. There was also an increase in sand (95%-98%) throughout the entire core.

EP-12 was primarily sand throughout the entire core (< 5% mud (silt and clay)). Much like EP-10, EP-12 exhibited a coarsening upward trend throughout the core with increased fine-grained (silt) particles at 32-28, 22-16, 6 cm, and at the surface.

Working up-core from the sandy base in EP-17, there were two finer grained layers with increased organic material at 42 cm and 34 cm. There was a gradual coarsening upward sequence from 46 cm to 16 cm. Directly above the fining upward sequence, there was an increase in grain size (sand) from 15 cm to 10 cm. The sediment in the surface section (10 cm to the surface) was slightly finer than the 15 cm to 10 cm section.

Throughout EP-18, the dominant sediment constituent was medium-fine quartz sand. The percent silt fluctuated between 1%-9% throughout the core.

The entirety of EP-19 was primarily quartz sand. There was a coarsening upward sequence from the base of the core to 22 cm. There was another, more

Table 2 Sampling site information including core name, recovery length, location and water depth.

Core name	Recovery (cm)	Latitude	Longitude	Water depth (m)
EP-09	24	27.52947	82.62617	1.3
EP-10	31	27.53257	82.64657	2.1
EP-12	41	27.53264	82.64282	2.7
EP-17	46	27.50892	82.59028	4.5
EP-18	42	27.49790	82.52267	2.6
EP-19	43	27.51932	82.48901	2.4

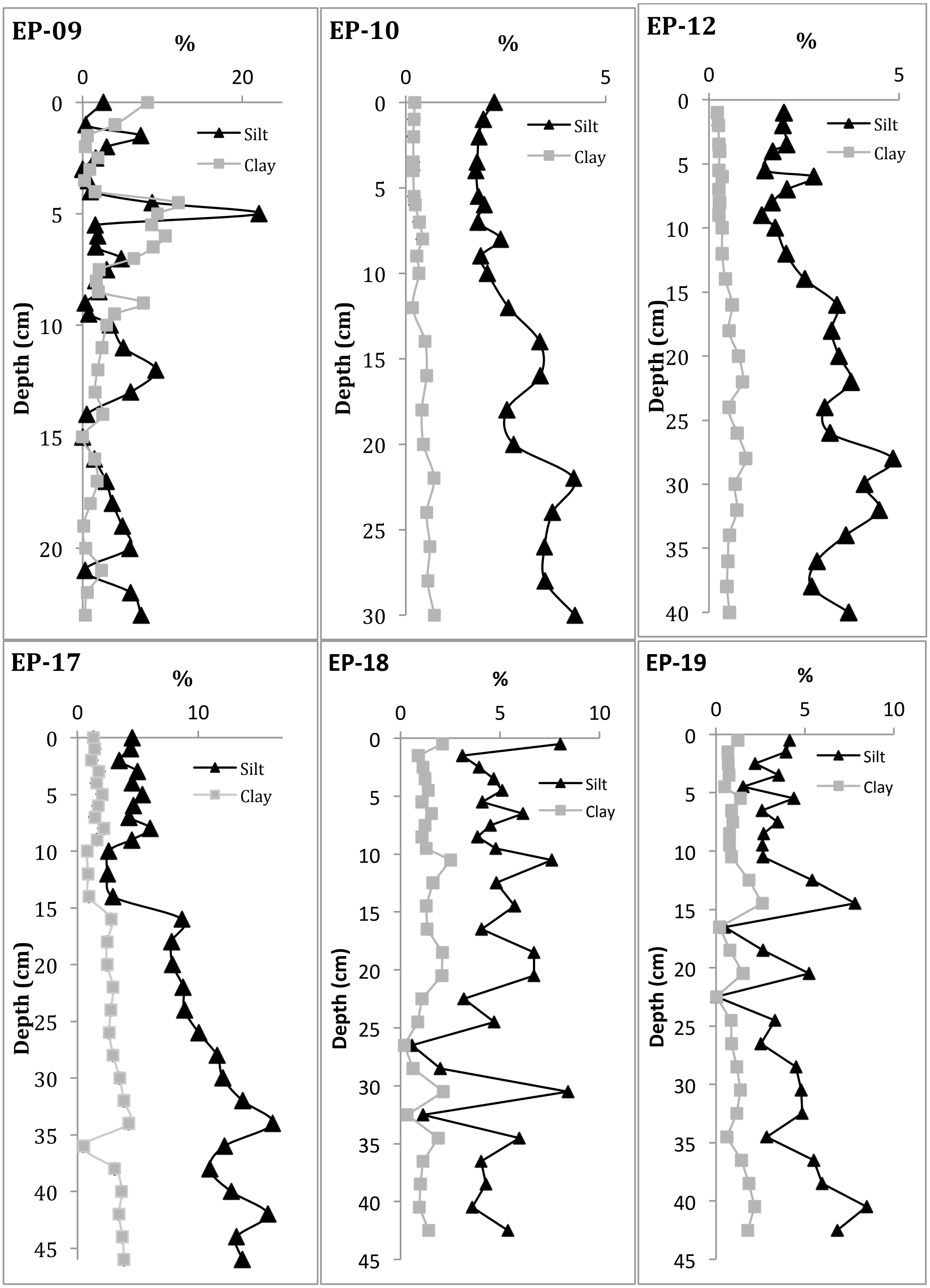

Fig. 3 **Grain size records for the six selected core sites in weight percentage of the silt and clay fraction.**

subtle, coarsening-upward sequence from 14 cm to 10 cm. The surficial unit of EP-19 was fairly constant with respect to texture (10 cm to the surface). Even in this core, being the farthest landward extent of the sediment core transect, there was evidently a coarsening-upward sequence throughout the core. This is similar to many of the seaward sampling sites.

4.2 Radioisotope Analysis

The excess ^{210}Pb record from EP-9 showed a gradual increase from background activity at 23 cm up-core (0-22.4 dpm/g), with several periods of low activity (9-12 cm and 5-7 cm) (Fig. 4). The ^{137}Cs record had increased activity from 17 cm to 11 cm (1951-1964) and a few lower activity peaks up-core at 5.5 cm to 4.5 cm and 1.5 cm to 0.5 cm. The results from the CRS model showed an initial slope of accumulation with a LAR of 0.22 cm/year from the base of the core to 20 cm (1906-1941). This slope increased (increased accumulation) to a LAR of 0.31 cm/year from 20 cm to 9.5 cm (1941-1968) and was followed by a rapid decrease in slope from 9 cm to 7.5 cm. The slope steepens again from 7.5 cm to 5 cm (1976-1982). There was a low slope from 5 cm to 1 cm (1982-2005) with a LAR of 0.17 cm/year. The average LAR for the entire core was 0.25 cm/year.

The ^{210}Pb record from EP-10 gradually increased from background at 28 cm to the surface of the core (0-26.6 dpm/g). There was depletion in activity (< 1.0 dpm/g) from 18 cm to 14 cm. The ^{137}Cs record showed the earliest activity at 20 cm and subsequent activity more recently at 12, 9, 7 and 2 cm. The earliest activity in this core was corroborated by the CRS model and occurred at some point between 1958 and 1970. There were two main periods of accumulation. The first occurred from the base of the core 30 cm to 20 cm depth (1904-1970) with a LAR of 0.23 cm/year. The second occurred from 20 cm to the surface of the core (1970-2009) with a LAR as high as 0.89 cm/year. The average LAR for the entire core was 0.58 cm/year.

The ^{210}Pb activity in EP-12 increased from background at 20 cm to the surface (0-22.6 dpm/g). There was depletion from 4 cm to 2 cm and was synchronous with increased ^{137}Cs activity from 5 cm to 2 cm (2000-2002). The ^{137}Cs record had low activity values at 16 cm and 14 cm (1941 and 1952, respectively) and a peak between 12 cm and 10 cm (1963-1979). There are three periods of accumulation. The first was from 16-18 cm where there was a relatively shallow slope (low accumulation), followed by a period of increased accumulation from 16 cm to 10 cm (1941-1979), much like EP-9. The third period of accumulation was from 10 cm to the surface (1979-2009) with an exponentially increasing slope and a slight decrease at 2 cm (2004).

The ^{210}Pb record from EP-17 increased from background at 20 cm to the surface (0-8.87 dpm/g) with a depletion of activity in the surficial unit (5 cm to the surface). The ^{137}Cs record increased in activity over the 16 cm to 12 cm interval, which corresponded to 1955-1972 in the CRS model. This corroborated the ^{210}Pb record, despite the depletion at the surface. The CRS model had only two main periods of accumulation at this site. The first was from 20 cm to 18 cm (1914-1943) with a LAR of 0.21 cm/year. Then, from 18 cm to the surface (1943-2009), the slope steepened, increasing to the surface with a LAR as high as 1.5 cm/year. The average LAR for the entire core was 0.50 cm/year.

The ^{210}Pb record from EP-18 was the most consistent and increased from background at 16 cm to the surface (0-9.11 dpm/g) with no major excursions. The ^{137}Cs record also follows exactly what was expected in that there are decreasingly large peaks in activity from 11 cm to 7.5 cm (1962-1986) and two small increases in activity towards the surface at 3 cm and 1 cm. The CRS model for this core had a gradual increase in slope throughout the core with LAR at the base (15 cm) of 0.14 cm/year and 1.23 cm/year at the surface (0.5 cm). This represented an order of

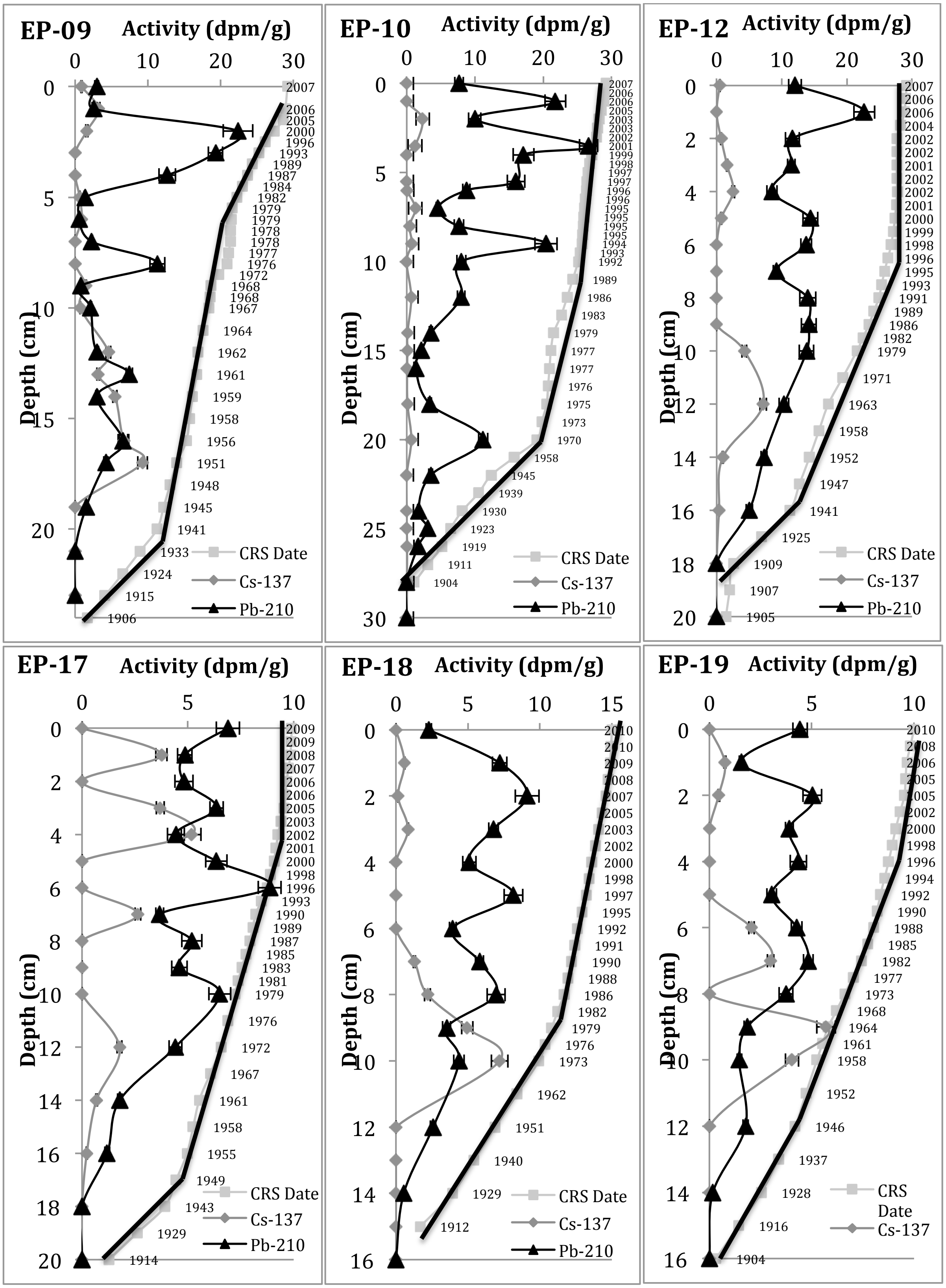

Fig. 4 ^{210}Pb and ^{137}Cs records along with the depth vs. date curve based on the CRS model from each of the six selected core sites.

magnitude increase in sedimentation rate within the last 100 years. The average LAR for the entire core was 0.40 cm/year.

The ^{210}Pb record for EP-19 increased from background at 16 cm to the surface (0-5.03 dpm/g) with only one significant excursion at 1 cm, which was also synchronous with an increase in ^{137}Cs. The ^{137}Cs record had high activity peaks from 10 cm to 6 cm (1958-1988) with the highest activity at 9 cm (1964). The CRS model was therefore corroborated by the ^{137}Cs record. The CRS model had two primary periods with the first occurring from 8-16 cm (1904-1973) and a LAR of 0.15 cm/year. The second period was from 0-8 cm (1973-2010) with a LAR as high as 0.38 cm/year. The average LAR for the entire core was 0.24 cm/year.

4.3 MARs

The MARs record from EP-9 showed episodic pulses of both terrigenous and carbonate material in 1941, 1956, and 2005 along with a continuous increase in both constituents from 1968-1979 (Fig. 5). The bulk accumulation rate was almost entirely composed of terrigenous material seeing as both are within 0.2-1.0 g/cm^2/year and covary throughout the entirety of the core. The accumulation rates of calcium carbonate (CO_3) and TOM were an order of magnitude lower between 0.00-0.07 g/cm^2/year.

The bulk accumulation rate from EP-10 was also dominated by terrigenous material with covariance throughout the core from 0.00-1.60 g/cm^2/year. The carbonate and organic accumulation rates ranged between 0.00-0.16 g/cm^2/year. All of the accumulation rates were relatively constant throughout the bottom of the core (1903-1969). The surface section of the core was marked by three features: (1) an increase in terrigenous and carbonate material from 1969-1983; (2) an increase in all constituents from 1989-1996; (3) a gradual increase towards the surface of the core in carbonate and terrigenous material from 2002-2007.

The relationship between terrigenous and bulk accumulation rates in EP-12 was similar to EP-9 and EP-10 and ranged between 0.19-1.12 g/cm^2/year. The carbonate accumulation rates were more than two orders of magnitude lower than terrigenous, while the TOM accumulation rate was much higher (0.004-0.07 g/cm^2/year) than the carbonate MARs (0.003-0.010 g/cm^2/year). Moving up-core from 1970-1998, the terrigenous and organic MARs roughly tripled and then decreased slightly from 1998-2003, where they both increased again from 2003-2007.

EP-17 had the highest terrigenous MARs of any of the cores (0.84-4.10 g/cm^2/year) which was fairly constant throughout the bottom of the core (1928-1975), decreasing slightly between 1975 and 1981 and then increasing throughout the surface section of the core (1981-2009). Carbonate and TOM MARs both increased from the bottom of the core (0.08-0.14 g/cm^2/year and 0-0.05 g/cm^2/year, respectively) and then gradually decreased from 1958-1981. They both increased along with the terrigenous MAR from 1981-2009. Terrigenous input to this site increased 3-fold over the last 100 years.

There was a gradual increase in all three main sedimentary constituents in the MAR record from EP-18 with terrigenous material ranging from 0.30-3.17 g/cm^2/year, carbonate material from 0-0.02 g/cm^2/year and organic matter from 0-0.03 g/cm^2/year. All three began to increase between 1961 and 1972. Slightly more organic matter accumulated between 1992 and 1997. Terrigenous input has increased in this area by an order of magnitude over the last 100 years.

The MARs records in EP-19 had a relatively constant input of organic and carbonate material (0-0.01 g/cm^2/year and 0-0.05 g/cm^2/year, respectively). However, there was a steady increase in terrigenous accumulation rate upcore (0.38-1.29 g/cm^2/year) resulting in an increase in accumulation rate of more than 4-times the rate in 1915.

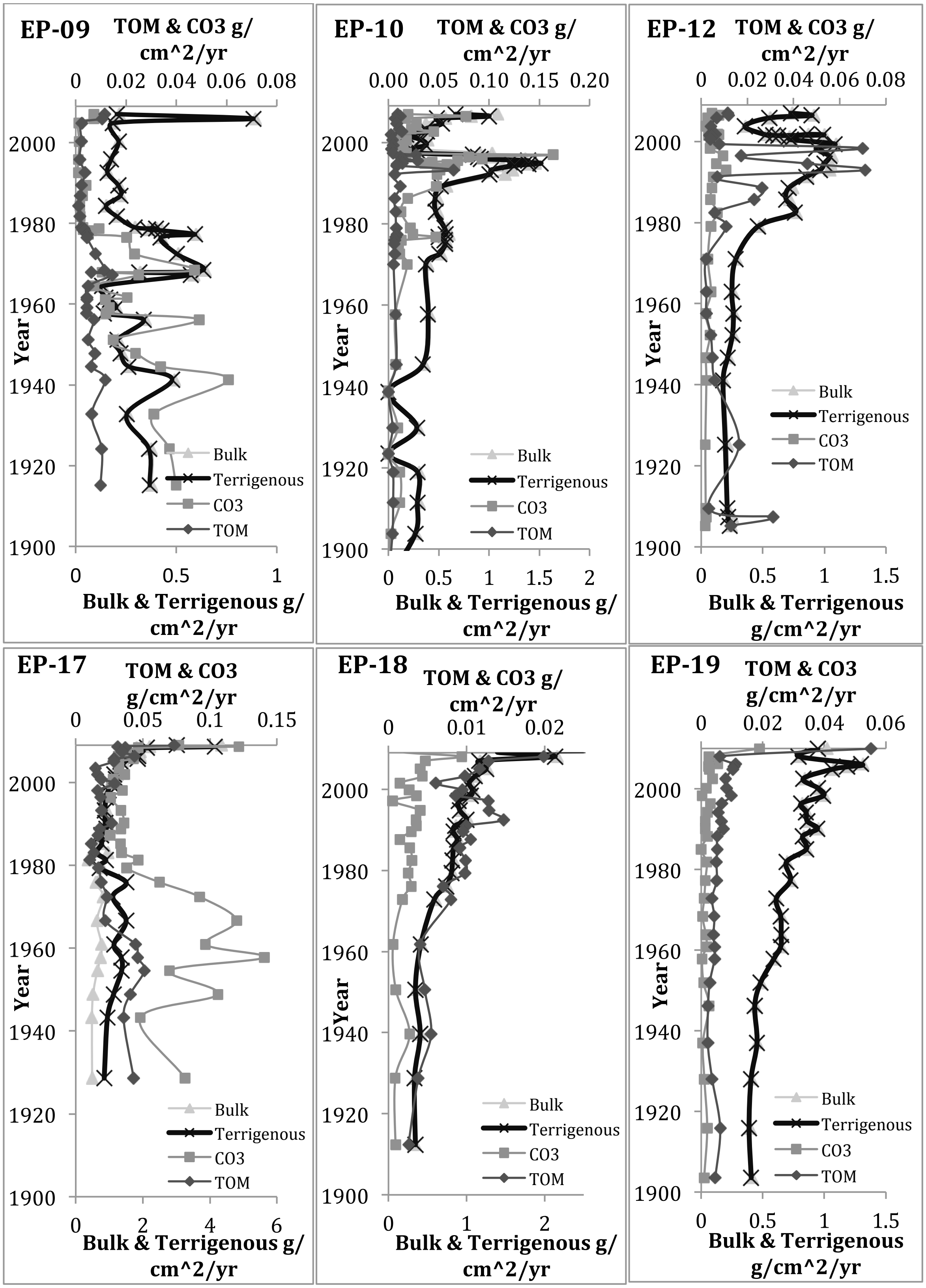

Fig. 5 MAR records for the six selected core sites including bulk, terrigenous, carbonate and TOM (note the change in scale on the x-axes).

5. Discussion

The radioisotope records provided a reliable geochronology for the upper extent of each core on which to interpret the changes in sedimentation rate and type. The corroboration (increased ^{137}Cs activity after 1950) between the ^{137}Cs and the ^{210}Pb-based CRS model in all cores supported the accuracy of the age models. The radioisotope records also helped characterize the anthropogenic influence on sedimentation. In the surficial 5 cm of every core, there were events where depletion in ^{210}Pb activity occurred synchronously with an increase in ^{137}Cs, which can be attributed to resuspension from elsewhere in the watershed. These resuspension periods were primarily due to increased terrigenous material introduced by anthropogenic development such as the construction of the I-75 bridge at EP-17 (9 cm), a jetty near site EP-9 (7 cm to 5 cm), the Manatee River Dam at site EP-9 (12 cm to 10 cm) and EP-10 (9 cm to 5.5 cm), and the construction of the US301 bridge at EP-9 (14 cm). The spread of urban development into previously agricultural lands was likely the cause for the resuspension events seen in the remainder of the cores that were farther inland (EP-12, EP-18, and EP-19).

In the Manatee River, most of the cores recorded three distinct periods of linear accumulation rate: (1) the predevelopment period with very low sediment accumulation (0.14-0.24 cm/year) (1900-1941); (2) the agricultural development period with gradually increasing sediment accumulation (0.21-0.35 cm/year) (1941-1970s); (3) the urban development period with quickly increasing sediment accumulation (0.39-1.51 cm/year) (1970s-2010) (Table 3). These linear accumulation rates were on the same order as those previously found in Florida (0.14-5.8 cm/year) [2, 6]. However, the change between the predevelopment and anthropogenic periods was much larger (2-10 times) than those found in previous studies (1-3 times) [10, 19].

The individual constituent MARs records improved upon the traditional LAR approach by providing a quantitative tool to assess changes in sedimentation by reporting the mass of each type of sediment constituent being deposited in each site over time. This approach was an improvement to the previous studies that have focused solely on LAR measurements because it accounts for compaction. Throughout the river, the primary source of sediment was terrigenous material (quartz sands and muds), as the terrigenous MARs were consistently an order of magnitude higher than both organic matter and carbonate material even at the base of the dated sediment column. Anthropogenic events were characterized in the MARs records by episodic to prolonged periods of increased terrigenous material. Episodic increases in each core were likely due to increases in local urban development. The terrigenous MARs from the base of each core to the surface increased dramatically. The surficial (2007-2010) terrigenous MARs varied from

Table 3 Linear accumulation rates (cm/year) from each site during each period of development (predevelopment, agricultural, and urban).

Core	Predevelopment LAR (cm/year) (1900-1941)	Agricultural LAR (cm/year) (1941-1970s)	Urban LAR (cm/year) (1970s-2010)
EP-09	0.23	0.30	0.46
EP-10	0.24	0.35	0.89
EP-12	0.20	0.27	0.84
EP-17	0.21	0.32	1.51
EP-18	0.14	0.27	1.23
EP-19	0.15	0.21	0.39

Table 4 Comparison of the terrigenous MAR at the base and the surface of each core.

Core	Base terrigenous MAR ($g/cm^2/year$)	Surface terrigneous MAR ($g/cm^2/year$)	% change
EP-09	0.36	0.88	144
EP-10	0.27	0.67	148
EP-12	0.23	0.72	213
EP-17	0.84	3.00	257
EP-18	0.30	2.13	610
EP-19	0.39	0.95	143

a 2-fold to 10-fold increase from the terrigenous MARs at the base of the column (~ 1900), with the largest increases occurring at the farthest landward sampling sites (EP-17, EP-18, and EP-19) (Table 4). This landward increase was likely due to the recent expansion of urban and agricultural development. The increase of bulk MARs is consistent with other coastal watershed sedimentation in the recent sedimentological record [1-12]. However, through the use of individual constituent MARs, this study has characterized the primary anthropogenic signal in the sediments of the Manatee River over the last 100 years as a 2- to 10-fold increase in terrigenous MARs.

6. Conclusions

The anthropogenic impact on the sedimentary system was inconclusive by only examining changes in the texture and composition of the core records. However, by producing a record of MARs based on short-lived radioisotope geochronologies, the anthropogenic signal became more apparent. The LARs in this study were on the same order of those found in past studies in Florida, but the increase between the pristine and anthropogenic periods was much larger. There were three periods of development evident in the sedimentary record of the Manatee River: (1) the predevelopment period (1900-1941); (2) the agricultural development period (1941-1970s); (3) the urban development period (1970s-2010). The MARs used in this study improved upon past linear accumulation rates by accounting for compaction and providing a more quantitative record of accumulation over time. Using MARs, the anthropogenic signal was represented by a 2-fold to 10-fold increase in terrigenous material over the past 100 years. Expanding urban and agricultural development has caused resuspension of sediments and increased the amount of terrigenous material deposited in the Manatee River by as much as an order of magnitude.

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