Available online at www.sciencedirect.com

SCIENCE DIRECT®

Estuarine, Coastal and Shelf Science 61 (2004) 211–227

ESTUARINE COASTAL AND SHELF SCIENCE

www.elsevier.com/locate/ECSS

Tracing organic matter sources and carbon burial in mangrove sediments over the past 160 years

Meagan Eagle Gonneea[a], Adina Paytan[a,*], Jorge A. Herrera-Silveira[b]

[a] *Department of Geological and Environmental Sciences, Stanford University, Stanford, CA 94305-2115, USA*
[b] *Centro de Investigacion y Estudios Avanzados del I.P.N., U. Merida, A.P. 73 Cordemex, Merida, Yucatan, Mexico*

Received 30 May 2003; accepted 28 April 2004

Abstract

Mangrove ecosystems may be a source of organic carbon and nutrients to adjacent coastal systems on one hand and provide a sedimentary sink for organic carbon on the other. The balance between these two functions may be sensitive to both natural and anthropogenically induced variability, yet these effects have not been thoroughly evaluated in mangrove ecosystems. We determine organic matter sources and carbon burial rates over the past 160 years in three lagoons on the Yucatan Peninsula, Mexico. Carbon isotopes and C/N elemental ratios are utilized to trace the three sources contributing to sedimentary organic matter, mangroves, seagrasses and phytoplankton, while nitrogen isotopes are used to elucidate potential post-depositional biogeochemical transformations in mangrove lagoon sediments. All three organic matter sources contribute to organic carbon burial. Phytoplankton and mangroves are the dominant sources of organic matter in lagoon bank sediments and seagrasses are a significant source to central lagoon sediments. Organic carbon burial rates are higher at the lagoon fringes, where mangrove vegetation dominates, than in seagrass-dominated mid-lagoon areas. A reduction in mangrove contribution to the sedimentary organic matter pool concurrent with reduced total organic carbon burial rates is observed in the recent past at all three lagoons studied. Natural cycles in sediment organic matter source over the past 160 years are observed in a high-resolution core. These fluctuations correspond to climatic variability in this region, as recorded in deep-sea foraminiferal assemblages. Additional work is required in order to differentiate between recent anthropogenic perturbations and natural variability in organic carbon sources and burial rates within these ecosystems.

Keywords: mangrove; seagrass; sediment; organic carbon; carbon burial; organic matter; isotopes

1. Introduction

Highly productive coastal mangrove ecosystems (average productivity of 2500 mg C $m^{-2} d^{-1}$) are strategically located at the interface between land and sea, and play an important role in the biogeochemical cycles of the coastal environment (Jennerjahn and Ittekkot, 2002). In particular, these systems may provide important nutrients and organic carbon (C_{org}) to tropical coastal oceans (Lee, 1995; Alongi, 1996). On the other hand, mangrove forests may intercept terrestrial-derived nutrients, pollutants and sediments before they reach the coastal ocean, alleviating problems due to high loading of these anthropogenic constituents (Valiela and Cole, 2002).

Mangrove forests are usually characterized by sediment accretion (Woodroffe, 1992). This fact, combined with the high productivity and low ratio of sediment respiration to net primary production, gives mangrove sediments the potential for long-term sequestration of C_{org}, thus these systems play an important role in the global carbon (C) cycle (Jennerjahn and Ittekkot, 2002). The balance in these multiple functions as an organic matter (OM) source on short time scales and as a sedimentary C sink on longer time scales may be sensitive to climatic change and/or anthropogenic perturbations of mangrove ecosystems. Further understanding of the C biogeochemical cycling in these

---

[*] Corresponding author.
E-mail address: apaytan@pangea.stanford.edu (A. Paytan).

0272-7714/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ecss.2004.04.015

systems at present, and how it may have varied in the past, is very important in light of how quickly mangrove ecosystems are changing and disappearing (Valiela et al., 2001). The goal of this study is to understand sedimentary OM dynamics in three mangrove lagoons on the Yucatan Peninsula of Mexico over the past 160 years. We use C and N isotopes and C/N elemental ratios to trace OM sources to sediments within these systems and examine changes in and relationships between OM source and C_{org} burial rates through time in each of the lagoons.

1.1. Nutrient and carbon cycling in mangrove ecosystems

Many C and nutrient cycling studies in the mangal ecosystem focus on mangrove trees, as mangrove litter fall and root biomass have been implicated as the ultimate source of OM that is regenerated and the source of C and nutrients exported out of the system, as well as the source of stored OM in the sediments (Kristensen et al., 1995; Alongi, 1996; Bouillon et al., 2000). However, other components (e.g. seagrasses and phytoplankton) may be just as important as mangroves to C and nutrient cycles in these systems. Seagrasses have been mentioned as potential nutrient sources in studies of some mangrove ecosystems (de Boer, 2000; Holmer and Olsen, 2002), but their contribution to C_{org} storage has not been thoroughly quantified or evaluated even though their role may be significant. The net burial of OM in sediments is a function of both the deposition rate to the sediment and decomposition and regeneration within the sediment. The latter is a function of reactivity of the OM to be decomposed (e.g. vegetation source) and the sedimentary environment (burial rates, grain size, redox conditions, microbial populations, etc.) Research is needed to determine how anthropogenic and/or natural changes may influence OM preservation in mangrove lagoon sediments.

1.2. Tracing OM Sources

C and N stable isotopes and C/N ratios have been utilized in many estuarine studies to determine OM sources (Schultz and Calder, 1976; Thornton and McManus, 1994; Middleburg and Nieuwenhuize, 1998; Yamamuro, 2000; Graham et al., 2001). They have also been used for tracing mangrove OM transfer through estuarine food webs (Newell et al., 1995; Loneragan et al., 1997; Bouillon et al., 2000; Lee, 2000; Chong et al., 2001) and, in conjunction with other tracers, mangrove OM export to coastal sediments (Cifuentes et al., 1996; Dittmar et al., 2001).

The requirements for applying C and N isotopes and elemental ratios to study sedimentary OM sources are that (1) end member sources must be clearly differentiated from each other and (2) the end member signature should be preserved after burial (i.e. no post-depositional changes). The first requirement can be verified by analysis of end member vegetation, however the second requirement is harder to test (Middleburg and Nieuwenhuize, 1998). Tests for post-depositional alteration have been performed chiefly on sediments where only two end members were recognized—autochthonous, including primary production by surrounding vegetation, phytoplankton, microphytobenthos and chemoautotrophs, or allochthonous, including marine and/or riverine input, as well as anthropogenic runoff (Thornton and McManus, 1994; Middleburg and Nieuwenhuize, 1998; Andrews et al., 1998). In systems with more than two potential sources and with variable inputs in space and time, such as studied here, it is difficult to separate simple multiple end member mixing from the effects of post-depositional alteration. It has been suggested however, that C and N isotope ratios ($\delta^{13}C$ and $\delta^{15}N$) of OM in sediments with OM content of only a few dry weight percent (DW%) are not altered significantly during decomposition (Meyers and Ishiwatari, 1993). Thus, C and N isotopes may be good tracers of OM source in mangrove sediments (which typically have ~5 dry DW% C_{org}) (Loneragan et al., 1997; Bouillon et al., 2000; Chong et al., 2001). Despite the potential complexity of variable sources and potential diagenetic alteration of source signals, we assume that if sediment OM composition can be explained by mixing between known and well defined OM end member sources, OM diagenesis has not significantly changed the isotopic composition or C/N ratios of the OM sources (e.g. we adopt the simplest explanation of the data).

Studies using C/N ratios as tracers of different OM end member sources show that this ratio can be altered by many processes, including ammonification, nitrification and denitrification (Matson and Brinson, 1990; Thornton and McManus, 1994; Cifuentes et al., 1996; Andrews et al., 1998; Yamamuro, 2000; Graham et al., 2001). Increases in C/N ratios of sedimentary OM, relative to the source, over time or with depth in a core, which are commonly observed, have been interpreted as indicative of preferential loss of nitrogen (N) (Andrews et al., 1998), while little change suggests that C and N are mineralized or preserved at the same rate. Decreases in C/N ratios, which have also been observed in some sediment, were explained as a result of the absorption of organic or inorganic N onto silicate clay surfaces (Macko et al., 1993) or the incorporation of N by bacteria in decaying OM (Cifuentes et al., 1996). However, if little change in C/N is observed between living (sources) and decaying OM pools, as in this study, then this elemental ratio may be utilized as a tracer of OM sources.

It must be kept in mind, however, that any determination of OM source in the sediment will only reflect the component of the OM that is preserved and not the original flux to the sediment. For example, if mangrove C is more recalcitrant than seagrass C and is preferentially preserved (de Boer, 2000; Holmer and Olsen, 2002), then isotopic analyses of OM in the sediment may record higher contributions (burial) of mangrove C relative to seagrass C despite potentially higher input and regeneration of seagrass OM. Hence, it is only possible to determine the source of the residual refractory OM in the sediment. This fraction, however, is the component that is related to long-term C_{org} sequestration and therefore is of interest.

2. Materials and methods

2.1. Study sites

The coast of the Yucatan Peninsula, bordering the southern Gulf of Mexico, is dominated by mangrove forests (Fig. 1a). Shallow lagoons lined with mangrove vegetation run parallel to much of the coast and are separated from the sea by sand barrier islands or peninsulas that are between a few meters to over a kilometer wide (Herrera-Silveira and Comín, 1995). Due to the karstic geology of the region, there is practically no surface run-off and thus rivers are not a significant source of terrestrial OM or nutrients to the coastal lagoons. The Yucatan Peninsula has a tropical climate with an average temperature of 28.5 °C and annual rainfall ranges from 50 cm in dry areas to 90 cm in wet areas (Herrera-Silveira et al., 1998b).

Three lagoons were sampled during December 2000 and October 2001. Celestun Lagoon (area: 28 km^2) lies on the west coast of the Yucatan Peninsula, Mexico (Fig. 1b) (Herrera-Silveira, 1994). This lagoon is relatively undisturbed and has little influx of pollution, although the port of Celestun (population 4600) is located on the barrier peninsula (Herrera-Silveira, 1996). The lagoon shores (stations 6 and 16, Fig. 1b) are lined by a fringing mangrove forest of *Rhizophora mangle, Avicennia germinans* and *Laguncularia racemosa*. In the shallow inner and central parts of the lagoon (station 3, Fig. 1b), *Halodule wrightii* and *Ruppia* sp.

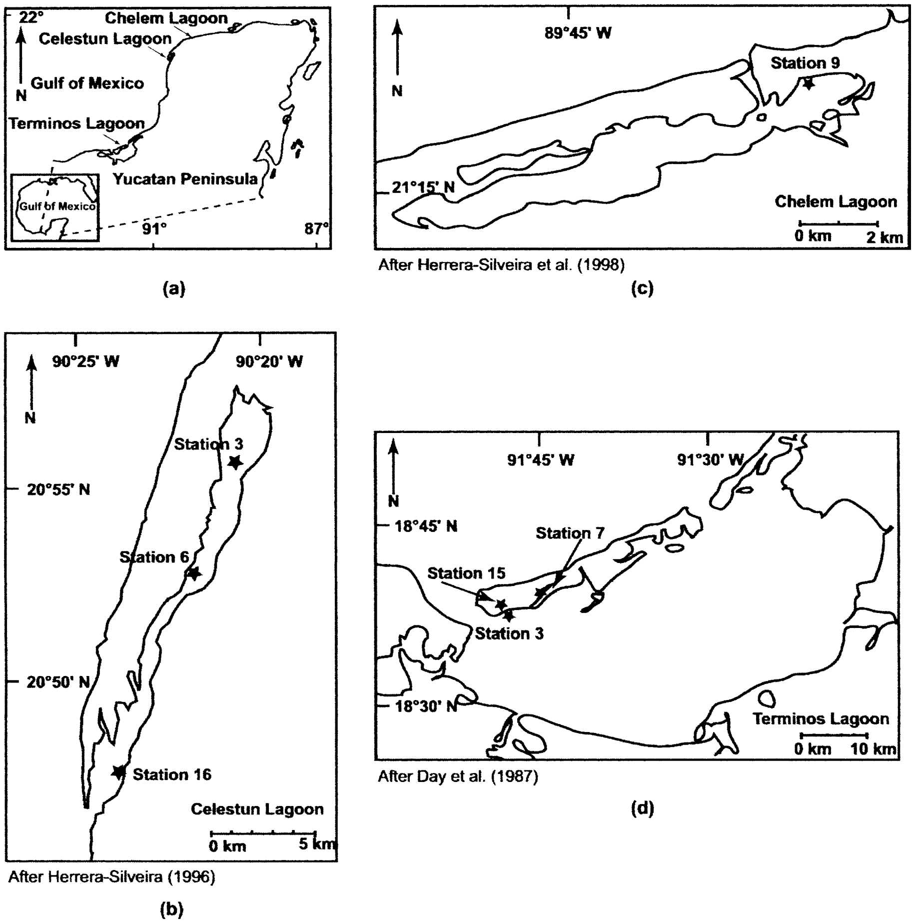


Fig. 1. Maps of (a) Yucatan Peninsula, (b) Celestun Lagoon, (c) Chelem Lagoon, and (d) Terminos Lagoon. Station locations are indicated by their respective designations. Note the different scales for each lagoon.

dominate extensive mid-lagoon seagrass beds, covering 65% of sediment surface area (Herrera-Silveira et al., 1998b).

Chelem Lagoon (area: 13.6 km^2) lies on the northwestern coast of the Yucatan Peninsula (Fig. 1c). The towns of Chuburna and Chelem and ports of Yucalpeten and Progresso surround the lagoon (population 25 000), and urban and industrial development has had an adverse impact on Chelem, resulting in a considerable reduction in vegetation cover (Herrera-Silveira et al., 1998b). Chelem was a hypersaline lagoon with only seasonal communication with the open sea through two natural openings until 1969, when Yucalpeten Harbor was created and another opening was added, increasing sea water exchange (Valdes and Real, 1998). Scrub mangrove forests dominated by dwarf *Rhizophora mangle* and *Avicennia germinans* line the northern and eastern shores of the lagoon (station 9, Fig. 1c), where the anthropogenic impact is greatest. Submerged aquatic vegetation, including seagrass (*Halodule wrightii*) and algae (*Chara fibrosa, Batophora oestedi, Chaetomorpha linum*), covers 37% of the sediment surface (Herrera-Silveira et al., 1998b), with greater coverage in the western part of the lagoon. Sediments in both Celestun and Chelem are dominated by autochthonous carbonate ooze.

Terminos Lagoon, at the southwestern base of the Yucatan Peninsula, is the largest estuary in Mexico (area: 2500 km^2, Fig. 1d). Carmen Island (38 km long and 2 km wide) forms a sand barrier between the lagoon and the open sea and is the location of Ciudad de Carmen (population 130 000). Terminos is the only lagoon in this study that receives riverine input. The lagoon is bordered by extensive fringe mangrove forests consisting of *Rhizophora mangle, Avicennia germinans* and *Laguncularia racemosa*, which give way to basin forests away from the lagoon edge. *Thalassia testudinum* beds are common in regions of the lagoon with clear water (station 3, away from river discharge, Fig. 1d).

Given the diversity of environments within Terminos Lagoon, from full seawater influence to full riverine, two tidal channels running from the lagoon into the barrier island with little riverine influence and similar ecosystems, but different degrees of anthropogenic influence, were chosen for this study in addition to one seagrass dominated site (station 3). Estero Pargo, the natural site (station 7, Fig. 1d, area: 0.5 km^2), is a channel with a fringe mangrove forest (Day et al., 1996). Station 15 is located on the banks of a channel (area: 0.2 km^2) that passes through Ciudad de Carmen (Fig. 1d). This channel is heavily polluted since the city is built right up to the edge of the channel, although large *Laguncularia racemosa* still line the bank. Sediments from both fringe mangrove sites in Terminos are dark brown organic rich silts mixed with some carbonate material, while seagrass sediments are autochthonous carbonate ooze. Sediment samples were collected at additional stations in all three lagoons, and data from these sites are plotted on the mixing diagrams but detailed depth profiles for all of these sites are not included in the present study.

2.2. Sediment and vegetation sampling and preparation

Sediment cores were collected during December 2001 and October 2002 using acrylic push cores (7 cm diameter, 30 or 50 cm length) and extruded and sectioned (2.5 cm intervals, except Chelem station 9 at 1 cm intervals) within 24 h of collection. Pore water was extracted by centrifugation from each interval and then sediments were dried at 50 °C and ground. Shells and any living biomass (including pneumataphors and propogules) were removed prior to grinding, as these components are growing in situ and thus not of interest for evaluation of sedimentary OM storage. Sediment samples were fume acidified with 10 N HCl to remove carbonates prior to isotope analyses (Yamamuro and Kayanne, 1995).

Vegetation samples (living and senescent) were collected from each lagoon and rinsed to remove sediment, salt and other plant debris. All plant samples were dried in a 50 °C oven within 24 h of collection with the exception of Terminos Lagoon vegetation samples, which were first frozen (for 3 days) and then dried. For seagrasses, only green leaves were used (except for samples labeled ‘senescent seagrass’). Stems were removed prior to grinding the mangrove leaves. Vegetation samples were ground and homogenized prior to analysis. Suspended particulate matter (SPM) was collect by low vacuum filtration of 1–2 l of lagoon water onto a pre-combusted Whatman GF/C glass fiber filter. SPM samples are considered representative of the phytoplankton end member, but may include microscopic fragments of other vegetation as well as zooplankton and some resuspended sedimentary material. Samples were split after grinding and homogenizing and one split was fume acidified with 10 N HCl to remove inorganic C (for δ^{13}C analysis) while the untreated fraction was used for δ^{15}N analysis.

2.3. C and N isotope and elemental ratio analyses

C and N isotopic analyses of OM in sediments were carried out at the Menlo Park USGS Stable Isotope Laboratory on a Micromass Optima continuous flow mass spectrometer. A Carlo Erba C-N-S elemental analyzer system is attached to the mass spectrometer for simultaneous analysis of DW% C_{org} and N_{total}. Vegetation samples were run at the Stable Isotope Laboratory at Stanford University on a Finnigan MAT isotope ratio mass spectrometer and a Carl Erbo NA1500 Series II elemental analyzer. Samples were run twice, acidified for δ^{13}C and un-acidified for δ^{15}N. C and N isotope abundances are reported in per mil deviations from a standard (PDB and atmospheric N respectively). Analytical precision is 0.1 and 0.5‰ for C and N, respectively. Sediment and vegetation C and N isotopes showed good reproducibility (0.3 and 0.9‰, respectively), determined by analysis of duplicate samples, when compared with the natural variability within each vegetation type (see Table 1). DW% C_{org} and N_{total} were determined at the same time as the isotopic compositions, but were not determined for SPM samples because samples were collected on a volume and not a weight basis.

2.4. *Sediment ages and C burial rates*

To establish a chronology for cores collected from these lagoons, sediment accumulation rates (SAR) were determined from ^{210}Pb profiles in 1 to 2 cores from each lagoon for which we present detailed depth profiles. Cores from Celestun were measured by low-level gamma counting at the Institute for Ocean Management, Anna University, India. ^{210}Pb values for cores from Terminos and Chelem were measured by low-level gamma counting at the Coordinated Instrumentation Facility of Tulane University. Since SAR can be underestimated without correcting for compaction, SAR were normalized to bulk densities (BD) following Lynch et al. (1989). SAR for the three lagoons range from 2 to 4 mm yr^{-1} (200–400 cm kyr^{-1}), and compare favorably with a previously published sedimentation rate (2.9 mm yr^{-1}) for the fringe mangrove forest at Estero Pargo, Terminos Lagoon (Lynch et al., 1989). C_{org} burial rates were calculated by multiplication of DW% C_{org} by the sediment mass accumulation rate (C_{org} burial = SAR × BD × DW% C_{org}).

Table 1
Average values of $\delta^{13}C$, $\delta^{15}N$ and C/N and one standard deviation for mangroves (including species *Rhizophora, Laguncularia*, and *Avicennia*), senescent mangrove leaves, seagrasses (including species *Ruppia, Halodule*, and *Thalassia*), senescent seagrass leaves and SPM for (a) Celestun Lagoon, (b) Chelem Lagoon, (c) Terminos Lagoon and (d) all lagoons

	$\delta^{13}C$		$\delta^{15}N$		C/N		*n*
	Average	SD	Average	SD	Average	SD	
(a) Celestun							
Mangrove	−28.79	1.35	6.80	3.14	57.9	28.7	19
Senescent leaves	−28.46	0.93	10.05	1.34	71.7	33.3	3
Seagrass	−15.36	2.33	7.75	2.59	20.4	2.3	7
Dead seagrass	−16.91	n/a	5.21	n/a	20.0	n/a	2
SPM	−22.06	2.80	7.78	1.87	8.7	1.5	8
(b) Chelem							
Mangrove	−26.55	1.25	7.89	3.16	53.8	24.7	9
Senescent leaves	−27.58	n/a	11.58	n/a	67.0	n/a	2
Seagrass	−16.23	0.36	11.74	2.89	21.2	0.6	3
Dead seagrass	−14.57	n/a	7.41	n/a	20.0	n/a	2
SPM	−22.06	2.80	7.07	2.27	9.3	0.9	5
(c) Terminos							
Mangrove	−28.93	2.00	4.31	3.55	53.4	14.9	6
Senescent leaves	−28.53	0.72	5.33	5.83	69.6	44.5	3
Seagrass	−11.88	n/a	−1.56	n/a	15.3	n/a	2
SPM	−25.32	3.91	4.45	1.93	7.3	0.8	6
(d) All lagoons							
Mangrove	−28.24	1.75	6.79	3.43	55.5	28.5	34
Senescent leaves	−28.33	1.17	9.75	3.21	76.0	34.1	8
Seagrass	−14.74	2.47	7.62	4.96	19.8	2.4	12
Dead seagrass	−15.74	2.30	8.97	3.04	21.4	2.0	4
SPM	−22.31	4.15	6.58	2.53	8.5	1.4	19

n, number of samples; n/a, not applicable.

2.5. *Ternary mixing diagram*

The lagoons in this study primarily receive OM from three sources—mangrove, seagrass and phytoplankton (referred to as SPM) production (Herrera-Silveira et al., 1998b). A ternary diagram has been employed to calculate OM sources. In this model each OM source occupies a corner of a triangle (Dittmar et al., 2001). Samples within the triangle defined by end members A, B and C (here mangroves, seagrasses and SPM) can be considered a mixture of these three sources. Samples that fall along any of the tie lines connecting two end members are a mixture of only those two OM types. Samples that fall outside of the triangle area indicate the presence of additional sources or diagenetic alterations of the original signal and cannot be characterized by this model. Following the example included in Dittmar et al. (2001), it is possible to expand the applicability of this model by establishing a tolerance interval (τ) such that:

$$\tau = \frac{a'}{a} \times 100\% = \frac{b'}{b} \times 100\% = \frac{c'}{c} \times 100\% \qquad (1)$$

where τ is the tolerance interval (%) which determines the range of values that may still be considered as defined by the three end member mixing model; *a, b* and *c* characterizing the strict validity of the model, and a', b', c' characterizing the expanded validity of the model (e.g. values acceptable within natural variability and analytical error). In our study, each ternary plot is expanded by a 10% tolerance level (see the empty circles in Fig. 3a–d). Samples that fall outside of the strict validity of the model, but within the expanded area (tolerance interval), are treated the same as samples that fall on the tie-lines and are a mixture of only two sources. Samples that fall outside of the strict triangle at the vertices but are within the expanded triangle are attributed completely to the source at the vertex.

3. Results and discussion

3.1. *End member vegetation isotopes*

Vegetation samples show considerable spread in isotope ratios within each group, representative of the natural variability, however a clear separation between vegetation groups is observed (Table 1 and Fig. 2). Significance values (Student's *t*-test, $P < 0.05$) between each species and between groups of primary producers from all three lagoons are reported in Tables 2 and 3. The different mangrove and seagrass species are not significantly different from each other based on their $\delta^{13}C$, $\delta^{15}N$ or C/N so have been grouped together to represent the mangrove and seagrass end member components respectively (see the filled triangles in Figs. 2 and 3). Mangrove, seagrass and SPM $\delta^{13}C$ values and C/N ratios are significantly different from each other (e.g. distinct end members). $\delta^{15}N$ values for the different vegetation groups are indistinguishable from each other and express considerable variability. One explanation for this observation is that N sources for mangroves, seagrasses and SPM (most likely NO_3^- and NH_4^+) all have the same isotopic signature. SPM samples have an average $\delta^{13}C$ (−22.31‰) and C/N ratio (8.5) within the range expressed by marine phytoplankton, so for the purpose of this study SPM is considered to be representative of the phytoplankton end member (Fry and Sherr, 1984; Yamamuro, 2000). Mangroves and seagrasses also have average $\delta^{13}C$ values (−28.24‰ and −14.74‰, respectively) and C/N ratios (55.5 and 19.8, respectively) in agreement with previously published data (Fleming et al., 1990; Cifuentes et al., 1996).

Previous studies have highlighted the importance of determining the effect of diagenesis on the OM tracers. We found that the senescent leaves from mangroves and seagrasses have $\delta^{13}C$ values within the variability expressed by living leaves. $\delta^{15}N$ of senescent mangrove leaves, on the other hand, was significantly heavier, 9.75‰ compared to 6.79‰ (Tables 2 and 3), likely as a result of selective regeneration of certain N containing compounds in the sediments and preferential preservation of mangrove OM with a heavier $\delta^{15}N$ (Fogel et al., 1989). The C/N ratio increased in decaying mangrove leaves from an average of 55.5 in intact leaves to 76.0 in fallen leaves, although this did not occur in every senescent leaf sample, so was not significant, but is consistent with the interpretation of the change in $\delta^{15}N$. Decaying seagrass (*Thalassia testudinum* and *Halodule wrightii*) collected on the sediment surface or floating in the lagoon water, also displayed a slight increase in $\delta^{15}N$ (8.97‰) compared to living species (7.62‰), although this was not significant (Tables 2 and 3). The C/N of decaying seagrass leaves was also slightly but not significantly higher (21.4) than living leaves (19.8). While $\delta^{15}N$ is not useful in differentiating OM sources, it does show some utility in evaluating the degree of diagenesis of OM and may highlight potential diagenetic processes that affect N cycling in these systems.

3.2. Sedimentary OM source in Celestun, Chelem and Terminos

The relative contribution of mangroves, seagrasses and SPM to sedimentary OM has been calculated using ternary mixing diagrams depicting the $\delta^{13}C$ and N/C values of the vegetation end members. Although little variation was found in vegetation $\delta^{13}C$ and N/C between the three lagoons, plant samples specific to each lagoon were used to determine end member values

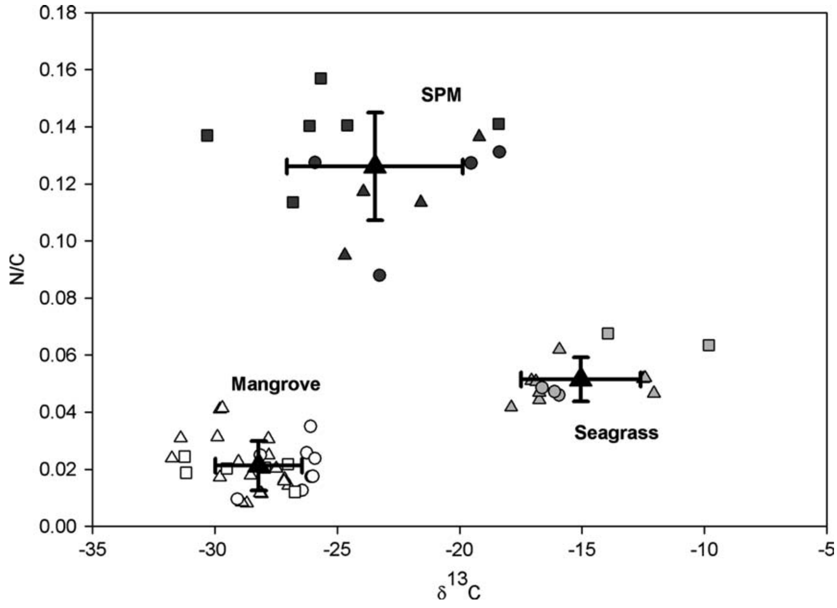


Fig. 2. N/C vs. $\delta^{13}C$ of lagoon vegetation; empty symbols for mangrove samples, light gray symbols for seagrass samples, dark gray symbols for SPM samples. The average of all vegetation end members are shown in black triangles with bars denoting one standard deviation. Celestun vegetation samples are represented by triangles, Chelem by circles and Terminos by squares.

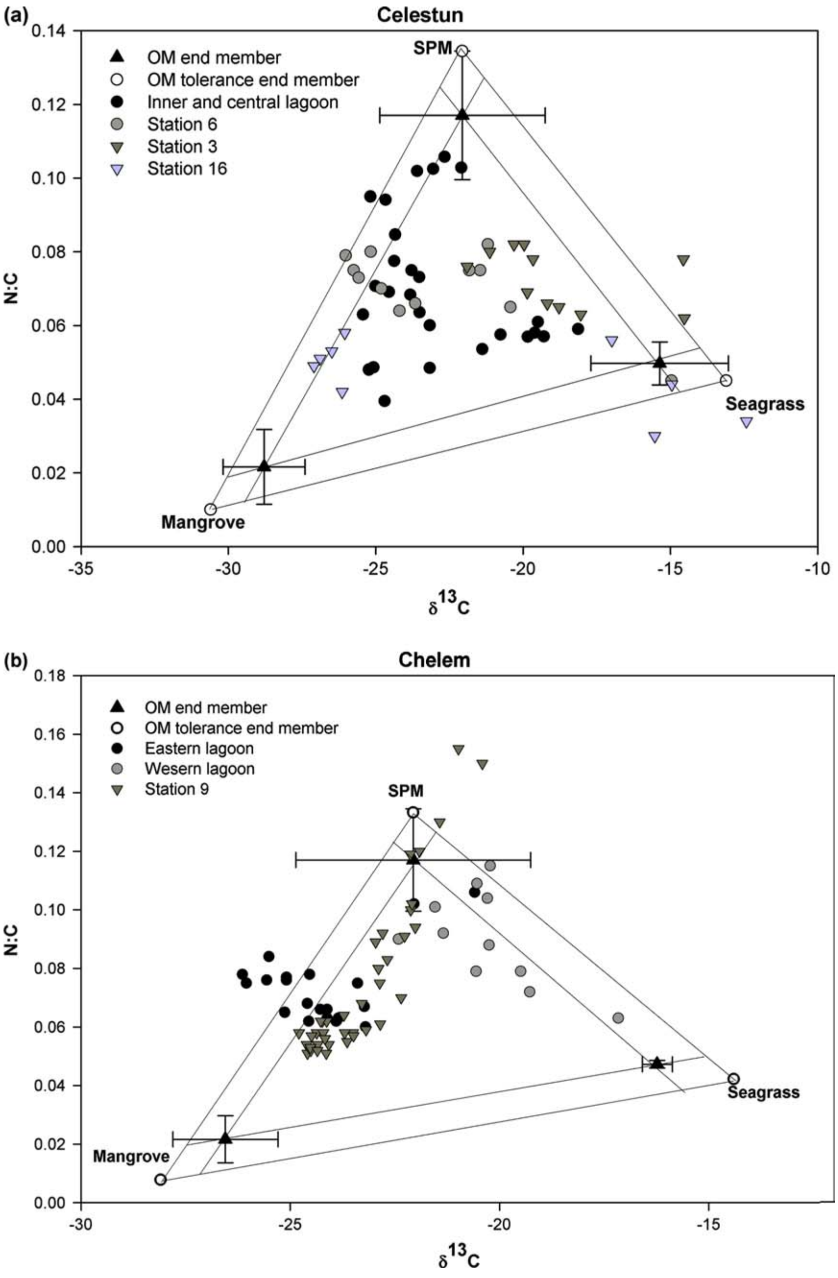


Fig. 3. N/C vs. $\delta^{13}C$ in ternary mixing diagrams of mangrove, seagrass and SPM OM. (a) Celestun Lagoon, including sediment samples from the inner and central region of the lagoon in addition to stations 3, 6 and 16; (b) Chelem Lagoon, including sediment samples from the eastern and western lagoon in addition to station 9; (c) Terminos Lagoon and (d) Terminos Lagoon with vegetation end members specific to station 3. Filled triangles are average end member values (Table 1, part d); empty circles are end member values expanded by a 10% tolerance level. In (a), (b) and (c), one standard deviation in N/C and $\delta^{13}C$ is indicated with bracketed lines for each end member. End member values for seagrass and SPM in (d) are based on single vegetation samples collected at station 3; mangrove end member is same as (c).

for each site. Accordingly, sediments from each lagoon are plotted on separate mixing diagrams (Fig. 3a–d). N/C ratios were used rather than the more common C/N to normalize against C. When plotted on these ternary plots, including both core tops and down core samples, 91% of Celestun sediments (Fig. 3a), 84% of Chelem sediments (Fig. 3b) and 65% of Terminos sediments (Fig. 3c) can be explained in terms of the three OM sources (e.g. mangroves, seagrasses and SPM). When a site-specific (rather than lagoon-wide) ternary plot is used for station 3 in Terminos (Fig. 3d), the mixing model explains100% of the OM in Terminos sediments. Sediment samples from throughout these lagoons are included in the ternary mixing plots to show the lagoon-wide applicability of the mixing model and also to highlight slight differences in relative contributions from the three vegetation end members to OM burial within each lagoon.

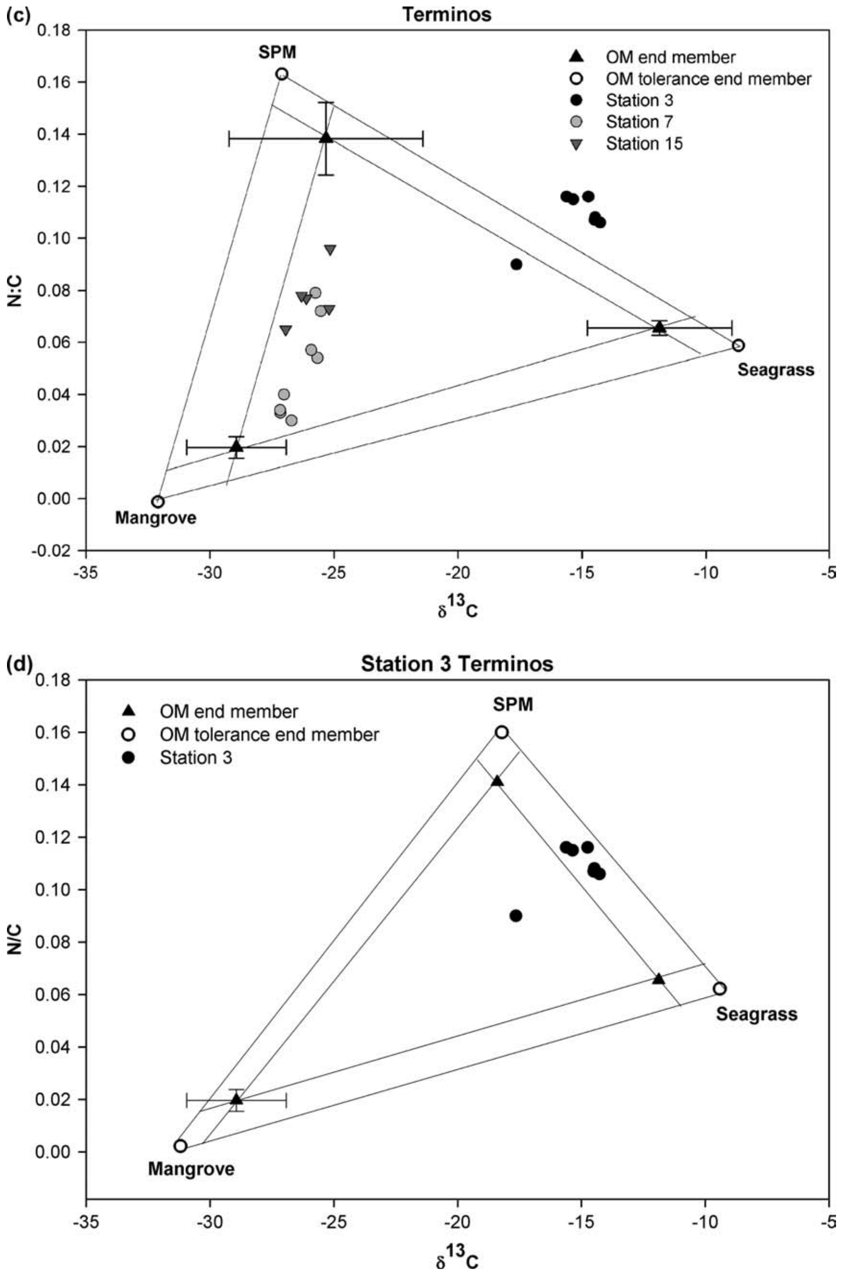


Fig. 3. (*continued*)

There is considerable intra-lagoon variability in OM $\delta^{13}C$, $\delta^{15}N$, DW% C_{org}, DW% N_{total}, C/N and C_{org} burial rates (Fig. 4), chiefly as a function of the dominant vegetation type at the core site or possibly site specific sediment biogeochemical properties affecting OM regeneration. This spatial variability is greatest between seagrass and mangrove-dominated sites, and, at Terminos, also between natural and impacted sites.

3.2.1. Celestun Lagoon

Sediments from Celestun Lagoon are plotted in Fig. 3a. There is considerable variability in the relative contribution of OM source within Celestun Lagoon at present and in the past. Regions of the lagoon dominated by fringe mangroves (station 6, Fig. 4b) have a lower $\delta^{13}C$ (−24‰) compared to values in the center of the lagoon farther from the mangroves (station 3, −20‰, Fig. 4a). As expected, the two fringe mangrove sites (stations 6 and 16) derive most of their OM from mangroves and SPM (although station 6 does receive significant seagrass OM at some intervals), while station 3, in seagrass beds, is dominated by seagrass and SPM OM. This distribution has not been previously documented although it is expected due to the greater

Table 2
P values from Student's t-test for statistical significance between mangrove, seagrass and SPM end members from all lagoons

	Mangrove			Seagrass			SPM		
	$\delta^{13}C$	$\delta^{15}N$	C/N	$\delta^{13}C$	$\delta^{15}N$	C/N	$\delta^{13}C$	$\delta^{15}N$	C/N
Mangrove	n/a	n/a	n/a	**<0.0001**	0.4595	**<0.0001**	**<0.0001**	0.4979	**<0.0001**
Seagrass	**<0.0001**	0.4595	**<0.0001**	n/a	n/a	n/a	**<0.0001**	0.9909	**<0.0001**
SPM	**<0.0001**	0.4979	**<0.0001**	**<0.0001**	0.9909	**<0.0001**	n/a	n/a	n/a

All vegetation samples from the three lagoons are included in these tests. Statistically significant values ($P < 0.05$) in bold.

contribution of seagrass and SPM C to OM in the center of lagoon, where sediments are covered with seagrass beds and lagoon waters are abundant with phytoplankton (both seagrass and SPM have heavier $\delta^{13}C$ than mangroves). The dominant sediment OM source appears to be a direct function of the overlying vegetation at each site; however, the presence of all three vegetation sources in sedimentary OM demonstrates that all three sources contribute to OM deposited throughout the lagoon.

3.2.2. *Chelem Lagoon*

Sediments from a core from station 9 on the eastern side of the lagoon and additional samples from the eastern (fringe mangrove site) and western (less impacted seagrass dominated site) lagoon are included in Fig. 3b. Although all three end members contribute to sedimentary C_{org} in Chelem, the distribution tends to fall close to the diagram tie lines, indicating that at each site only two end members dominate the OM burial (Fig. 3b). Cores from the western lagoon are dominated by seagrass and SPM, while samples from the eastern part typically lie closer to the mangrove-SPM tie line (Fig. 3b). As in Celestun, this is likely a function of the dominant vegetation source, as there is greater seagrass coverage in the western lagoon while mangroves dominate in the eastern lagoon. It is interesting that sediments from the upper portion of the cores collected at the eastern side of the lagoon seem to fall outside the diagram but close to the SPM vertex, which may suggest increased marine influence within the fringing mangroves after construction of the Yucalpeten Harbor in 1969. Alternatively, as suggested by a higher N/C (lower C/N) than expected from their $\delta^{13}C$ signature, this result could potentially be caused by bacterial activity in the sediments at this location, or adsorption of N from other, possibly anthropogenic, sources onto the sediments, as has been observed previously (Cifuentes et al., 1996).

Table 3
P values from Student's t-test for statistical significance between living and senescent mangrove and seagrass leaves from all lagoons

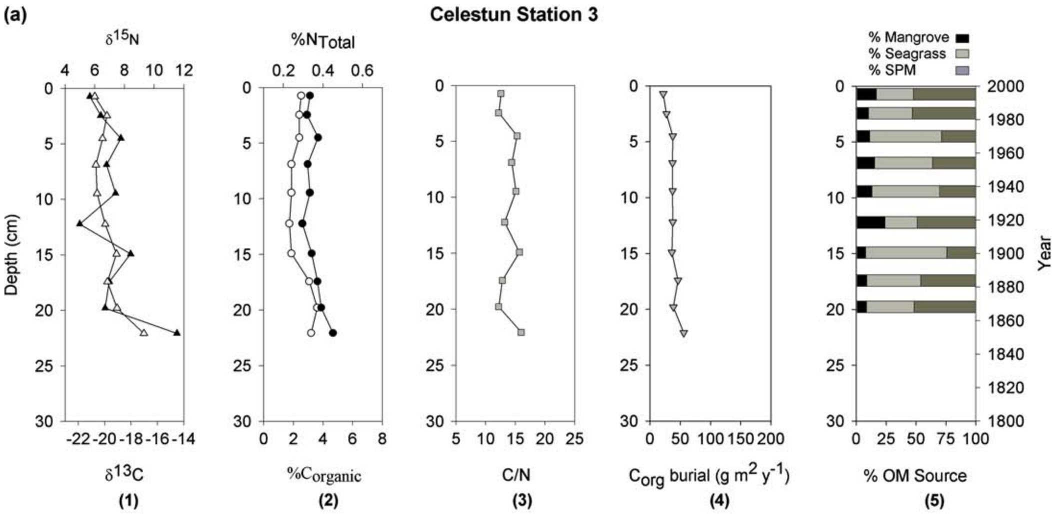
Mangrove	Senescent Leaves			Seagrass	Senescent leaves		
	$\delta^{13}C$	$\delta^{15}N$	C/N		$\delta^{13}C$	$\delta^{15}N$	C/N
Living leaves	0.8827	**0.0081**	0.0773	Living leaves	0.2449	0.2663	0.1082

All vegetation samples from the three lagoons are included in these tests. Statistically significant values ($P < 0.05$) in bold. n/a, not applicable.

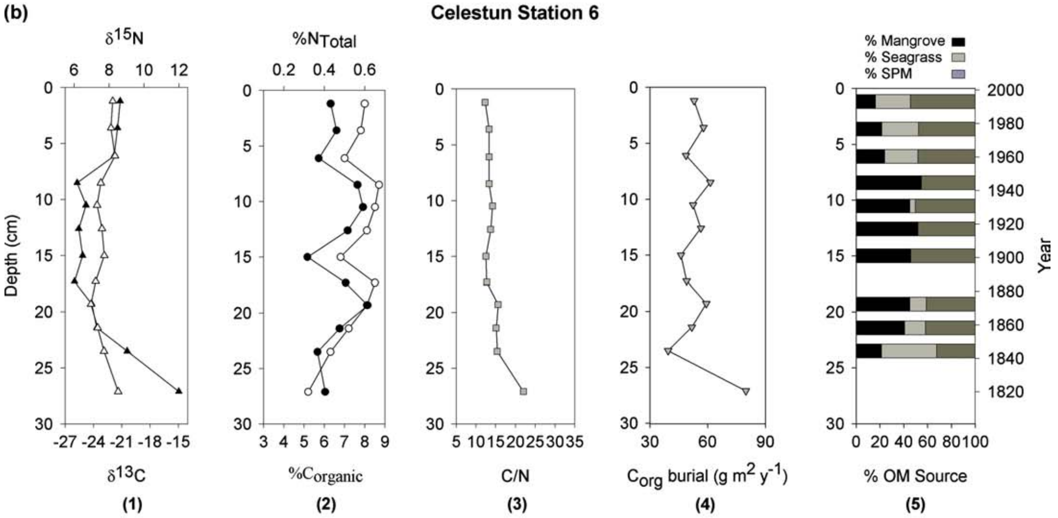
3.2.3. *Terminos Lagoon*

Sediments from the two fringe mangrove sites in Terminos Lagoon, station 7 (natural site at Estero Pargo) and station 15 (within the polluted Carmen channel) have $\delta^{13}C$ similar to mangrove OM (−26‰, Fig. 4f.1 and g.1), and derive most of their C_{org} from mangroves and SPM (Fig. 3c), with seagrass contributions only ~10%. This is not surprising since there are no seagrass beds nearby. Data from station 3, 50 m from the shore (outside the Ciudad de Carmen channel), falls outside the end member model based on all Terminos vegetation. This is an interesting result, and one possible explanation is diagenetic alteration of OM at this site. However, we did not find a significant difference in $\delta^{13}C$ or N/C between decaying seagrass and live seagrass at this site (Tables 2 and 3), although this observation should be confirmed with a greater number of samples. In addition, if during the processes of decomposing, OM preferentially looses N, as suggested previously (Andrews et al., 1998), the N/C of decomposed seagrass OM should decrease while the N/C ratios of station 3 sediments show an increase compared to the OM signal. Thus, decomposition is most likely not responsible for station 3 sediments falling outside of the model in Fig. 3c. As in the sediments from cores obtained from the eastern Chelem Lagoon, this result may be due to bacterial activity in the sediments or adsorption of N-rich OM from other sources, e.g. sewer (Cifuentes et al., 1996). However, when seagrass and SPM samples collected specifically at station 3 are plotted as the end members on a ternary mixing diagram, sediments do fall within the expanded validity of this model (Fig. 3d), in line with our observation about the relation between OM source and proximal vegetation. Indeed, at this mid lagoon site, heavy $\delta^{13}C$ values (−16‰) suggest that seagrasses and SPM are the main contributors to the OM pool with very little input of mangrove C_{org} (Fig. 4e.5). At this location, mangrove OM is effectively trapped

(a) Celestun Station 3



(b) Celestun Station 6



(c) Celestun Station 16

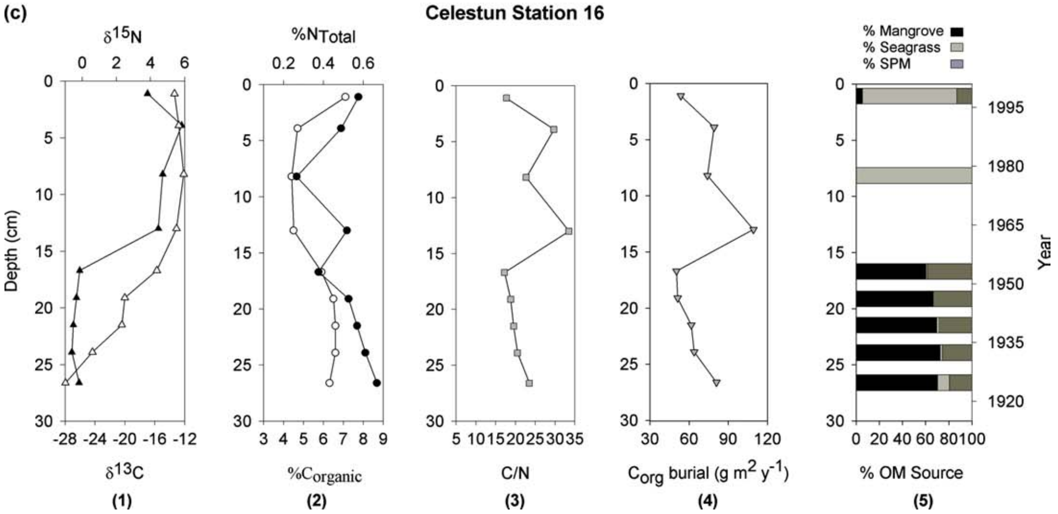
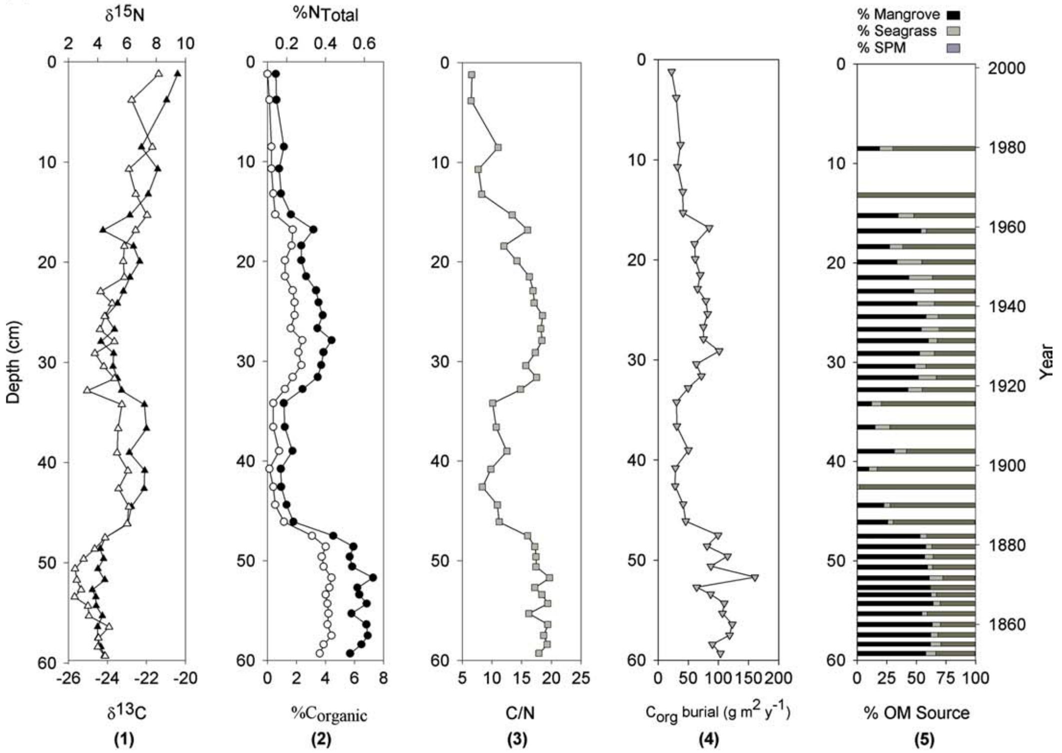
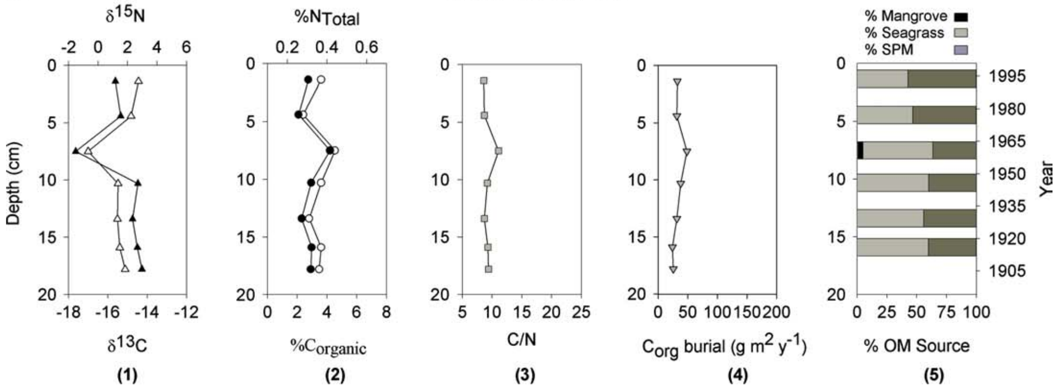


Fig. 4. Down core analyses. Core depth (cm) vs. (1) $\delta^{13}C$ (filled triangles) and $\delta^{15}N$ (empty triangles); (2) DW% C_{org} (filled circles) and DW% N_{total} (empty circles); (3) C/N elemental ratio; (4) C_{org} burial (C g m^{-2} yr^{-1}); and (5) OM source, % mangrove is black, % seagrass is light gray and % SPM is dark gray. Note that samples that fall outside of the ternary mixing diagram (Fig. 3) are not included in (5). (a) Celestun station 3, (b) Celestun station 6, (c) Celestun station 16, (d) Chelem station 9, (e) Terminos station 3, (f) Terminos station 7 and (g) Terminos station 15. Note the expanded C_{org} burial scales in (c.4), (d.4) and (f.4) and the expanded DW% C_{org} scale in (f.2).

(d) **Chelem Station 9**



(e) **Terminos Station 3**



(f) **Terminos Station 7**

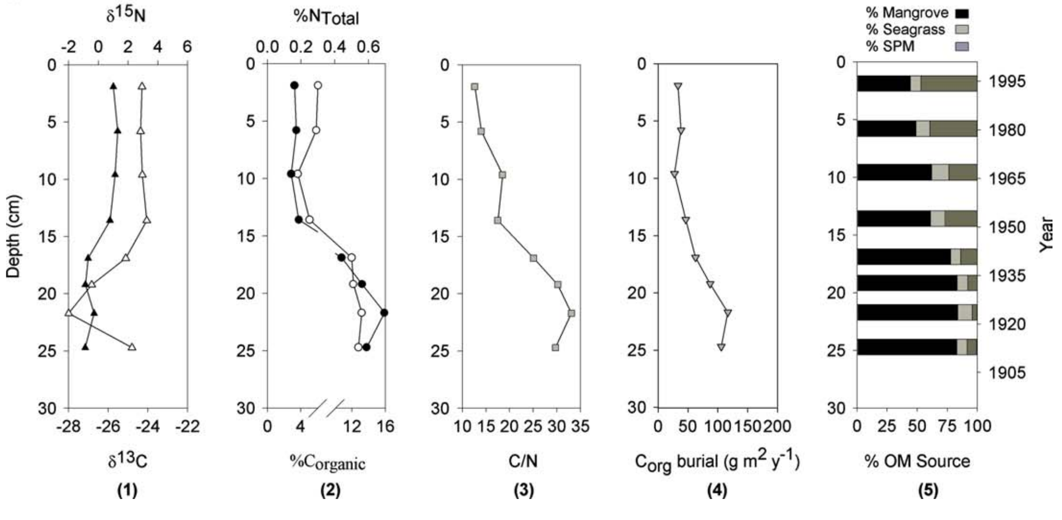


Fig. 4. (*continued*)

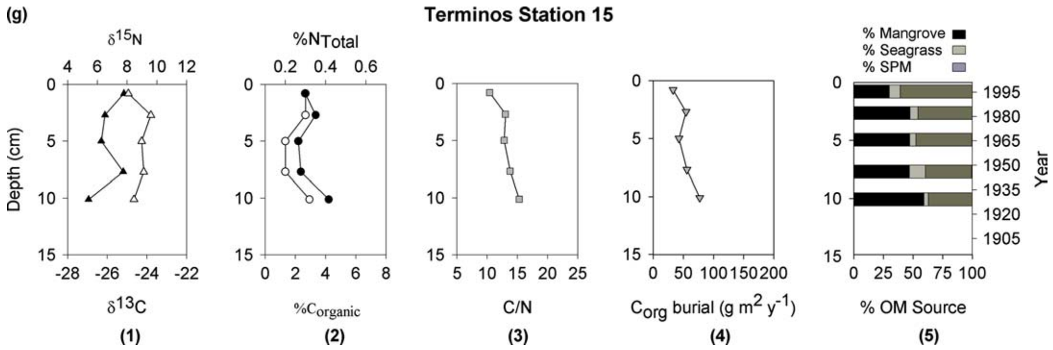


Fig. 4. (*continued*)

along the shore, within the fringe mangrove sediments, suggesting that all degradation and nutrient recycling of mangrove C_{org} occurs in the fringe mangrove sediments, with little mangrove C_{org} deposition away from the lagoon shore, let alone exported to the adjacent coastal ocean (at least at present). Variability in $\delta^{13}C$ and N/C within Terminos Lagoon vegetation limits the applicability of a lagoon-wide OM source model to specific environments within the lagoon, and the same end member values cannot be used throughout the lagoon, unlike the lagoon-wide applicability of the mixing models for both Celestun and Chelem.

In Terminos sediments, the $\delta^{15}N$ of OM may be sensitive to anthropogenic influence. Unpolluted sites in Terminos (stations 3 and 7) have mangrove, seagrass and SPM with much lower $\delta^{15}N$ than the polluted site (station 15). For example, inside Estero Pargo (station 7), $\delta^{15}N$ of mangroves is 2.8‰ and of SPM is 4.4‰ and vegetation at station 3 exhibit $\delta^{15}N$ values of −3.1‰ for seagrasses and 1.4‰ for SPM, while the polluted Ciudad de Carmen channel mangroves and SPM have a $\delta^{15}N$ of 11‰ and 6.4‰, respectively. Thus, it is likely that N sources and cycling differ greatly between the polluted and unpolluted sites in Terminos Lagoon and that vegetation reflects the changing N dynamics at each location. The heavy $\delta^{15}N$ values of vegetation and sedimentary OM at the polluted site may be due to extensive denitrification processes within this system or input of anthropogenic N with a heavy isotopic signature (Kaplan and Cline, 1979; Mariotti et al., 1981; Spies et al., 1989; Rivera-Monroy and Twilley, 1996; Rogers, 1999). Alternatively, sediment OM isotopic signatures may be a reflection of the isotopic signature of the overlying vegetation, which may also be a function of the impacts on N signature mentioned above. Such wide variability in N isotopic values in vegetation and sediment are not observed in either Celestun or Chelem Lagoons but have been observed before at other polluted locations (Spies et al., 1989; Rogers, 1999).

3.3. Temporal variability in sediment isotopes, elemental ratios and C_{org} burial rates

Sediment depth profiles of OM $\delta^{13}C$, $\delta^{15}N$, DW% C_{org}, DW% N_{total}, C/N and C_{org} burial rates are shown for selected dated cores from Celestun, Chelem and Terminos Lagoons to highlight fluctuations in sedimentary OM composition through time and the relationship between OM composition and C_{org} burial rates (Fig. 4). To help visualize changes in OM source over time, the information provided by the ternary mixing diagrams is also shown plotted against core depth and year for each of the core profiles (Fig. 4a.5–g.5).

3.3.1. Celestun Lagoon

Temporal fluctuations at station 6, within the fringe mangrove, show a general trend towards lighter $\delta^{13}C$ and $\delta^{15}N$ between 7 and 20 cm in the sediment, when compared to the upper 7 cm, returning to heavier values at the bottom of the core (Fig. 4b.1). This may reflect shifts in the relative amount of mangrove contribution to the sediment from lower values (~20%) prior to 1900 to higher values (~50%) in the recent past, approximately from 1900 to 1940 and back to lower values at present (~20%) (Fig. 4b.5). Station 16, near the lagoon entrance, also records heavy $\delta^{13}C$ values (−16‰) in the top of the core (0–13 cm) and lighter values down core, indicating a switch from mangrove dominated sedimentary OM in the past (marked by $\delta^{13}C$ of −26‰ from 17 to 27 cm down core) to seagrass dominated OM at present (Fig. 4c.1). This drastic shift occurs around 1963, perhaps as a result of changes in lagoon circulation after infilling to construct a bridge across the lagoon around that time (Herrera-Silveira et al., 1998a). Periods of decrease in mangrove OM contribution to the sediment at the two fringe mangrove sites (stations 6 and 16) show an accompanied reduction in bulk C_{org} burial rates. These records may indicate temporal fluctuations in the overall lagoon vegetation distribution, however, more cores are needed to verify if these fluctuations are representative of lagoon-wide changes. In addition, longer cores are needed to verify if the observed transitions between low mangrove to high mangrove contributions that seem to occur on decadal time scales persist deeper in the record. Interestingly, at the mid lagoon, seagrass dominated site (station 3), spanning the same time interval (past 150 years), no obvious trend in the relative contribution of seagrass and SPM with time (depth) is observed. If representative, this trend may suggest that the mid lagoon, away from the fringe mangrove, is a relatively stable environment, less susceptible to processes that affect vegetation distribution or organic matter preservation in the sediment.

DW% C_{org} and DW% N_{total} tend to follow similar trends with depth in the cores (e.g. vary systematically within each core), thus C/N ratios do not demonstrate much change throughout the profile, although there are several outliers in station 16 (Fig. 4a.3–g.3). C_{org} burial fluxes are principally controlled by changes in the DW% C_{org}, and are overall lower in seagrass dominated mid-lagoon sediments (40 g C $m^{-2} yr^{-1}$) than in fringe mangrove sediments (55–70 g C $m^{-2} yr^{-1}$). This relation implies that changes in the contribution of mangrove OM to the sediment either as a result of changes in vegetation distribution or due to variable regeneration processes may significantly affect the total C_{org} burial rates in these systems.

3.3.2. Chelem Lagoon

The core collected at station 9 in Chelem offers a much higher temporal resolution record due to higher sedimentation rates (4 mm yr^{-1}) and finer sectioning (Fig. 4d). This site is located in the eastern, mangrove dominated, part of the lagoon, which has been highly affected by anthropogenic perturbations. Based on our isotopic analysis, it is possible to define four distinct intervals in this core. Interval one, from 0 to 15 cm (~1970 to 2001), displays $\delta^{13}C$ and $\delta^{15}N$ values of −22‰ and 6–8‰, respectively, along with very low DW% C_{org} (1%) and DW% N_{total} (0.1%). Interval two, from 15 to 33 cm (~1920 to 1970), has isotope excursions towards lower values ($\delta^{13}C$ of −24‰ and $\delta^{15}N$ of 4‰) accompanied by an increase in total OM (C_{org} is 2–4 DW% and N_{total} is 0.2 DW%). Interval three, from 33 to 47 cm (~1885 to 1920), is similar to interval one and exhibits a return to heavier isotope values ($\delta^{13}C$ of −22‰ and $\delta^{15}N$ of 5–6‰) and low OM content (C_{org} is 1 DW% and N_{total} is 0.1 DW%). Interval four (47–60 cm, ~1850 to 1885) is similar to interval two, with lighter isotope values ($\delta^{13}C$ of −24‰ and $\delta^{15}N$ of 3–4‰) and higher OM content (C_{org} is 6–8 DW% and N_{total} is 0.4 DW%). In addition, intervals one and three have a C/N molar ratio of 10–12, while C/N in intervals two and four are 16–18. This profile demonstrates the presence of cyclic changes in the processes affecting OM deposition in this lagoon. Mangroves contribute more to the refractory OM pool in the sediments during periods marked by lower isotope ratios (2 and 4), while SPM dominates during excursions to higher isotopic values (potentially suggesting increased marine influence or increased phytoplankton production in the lagoon itself) (Fig. 4d.5). In periods with greater mangrove contributions, C_{org} burial rates are about 50% higher (67–104 g C $m^{-2} yr^{-1}$) than in periods dominated by SPM contributions (35 g C $m^{-2} yr^{-1}$), caused by either higher preservation (mangrove OM is more refractory) or greater overall primary production. This 40–50 year cycle (based our ^{210}Pb-derived ages) mainly consists of variability in the relative contribution of mangrove and SPM OM sources, with seagrasses contributing a small and constant fraction of about 10–15% of the total sedimentary organic carbon. These changes may be related to regional climate changes that affect vegetation distribution and/or lagoon circulation and salinity (see Section 3.4).

3.3.3. Terminos Lagoon

Sediment profiles of polluted (station 15) and unpolluted sites (stations 3 and 7) display interesting contrasts, particularly in N isotopes (Fig. 4e–g). The fringe mangrove site in the unpolluted Estero Pargo (station 7) has a light $\delta^{13}C$ of −27‰, indicating C_{org} in the sediments is mainly from mangroves (Fig. 4f). There is a negative excursion in the $\delta^{15}N$ profile to −2‰ between 7.5 and 15 cm, with a return to core top $\delta^{15}N$ values (2‰) at the bottom. Over the same interval, the DW% C_{org} and DW% N_{total} steadily increase to a maximum 16% C_{org} and 0.5% N_{total}. Station 15, located within the polluted Ciudad de Carmen channel, is also dominated by mangrove carbon ($\delta^{13}C$ is −27‰) but has much heavier OM $\delta^{15}N$ (9‰) (Fig. 4g). Similar to station 7, there is a negative excursion in the $\delta^{15}N$ profile to −2‰ away from the baseline of 2‰, which also corresponds to a slight increase in DW% C_{org} and DW% N_{total}. These negative $\delta^{15}N$ excursions in stations 3 and 7, which correspond to higher DW% OM in the sediment, could be an indicator of bacterial activity in the sediment and possible contributions of C and N from the bacteria biomass present (Cifuentes et al., 1996). In Terminos, as in the other lagoons, we also observe that the fringe mangrove sediments have higher C_{org} burial (53–65 g C $m^{-2} yr^{-1}$) compared to mid-lagoon, seagrass-dominated sediments (33 g C $m^{-2} yr^{-1}$). Both the unpolluted and polluted fringe mangrove sites display a decrease in mangrove contributions to sedimentary OM, from 80% to 40% in the past 90 years at station 7 and from 60% to 40% in the past 35 years at station 15 (Fig. 4f.5 and g.5). This decrease is accompanied by a decrease in the C_{org} burial rates up core, from a maximum of 117 g C $m^{-2} yr^{-1}$ at 22 cm (1925) to only 34 g C $m^{-2} yr^{-1}$ at present in station 7 sediments and from 77 g C $m^{-2} yr^{-1}$ at 10 cm (1965) to 33 g C $m^{-2} yr^{-1}$ in the core top of station 15 (Fig. 4f.4 and g.4). Although, as with the trends observed in the other lagoons, these changes may be a result of natural vegetation changes, it is more likely that at this location the lower mangrove contribution is a result of human land use practices and urban development, which reduce mangrove forest density (Day et al., 1987).

3.4. Teleconnection with Cariaco Basin

To determine if the observed variability in sedimentary OM source is related to regional climatic fluctuations, we have compared the longer record from station 9, Chelem Lagoon, with a deep-sea foraminiferal (*Globigerina bulloides*) abundance record from the Cariaco Basin (Black et al., 1999). The abundance of *G. bulloides* is sensitive to upwelling in the Cariaco Basin, which in turn is a function of winds. The Cariaco Basin record exhibits decadal variability during the time period represented by the Chelem Lagoon core (see Fig. 3, (Black et al., 1999). We do not find a consistent relationship between these two records, although both exhibit variability on similar time scales. For the part of the record between 1850 and 1910, it is possible to see a correlation between the *G. bulloides* record and sedimentary OM source fluctuation (1853–1904, $r^2 = 0.78$, see inset in Fig. 5). During periods of SPM dominance and low mangrove OM contributions, *G. bulloides* abundances are high, i.e. stronger zonal (trade) winds in the southern Caribbean are observed. Changes in the wind patterns may result in precipitation changes and affect the water and nutrient balance in the lagoon, resulting in changes in vegetation distribution or in sedimentary OM regeneration processes. However, this relationship is not maintained throughout the record, in fact from about 1910 to the present this pattern is reversed, and periods of high mangrove and low SPM sedimentary OM contributions correlate to low *G. bulloides* abundances and vice versa (1922–1980, $r^2 = 0.37$). It is expected that mangrove ecosystems would respond to climatic fluctuations, however, the exact nature of the teleconnections cannot be speculated upon on the basis of this one record from Chelem Lagoon. In particular, other local factors possibly relation to population distribution and land use changes in the last century may have also contributed to the observed changes (Hodell et al., 1995; Curtis et al., 1996, 1998). Regardless, the observed fluctuations are intriguing and warrant more and longer records to be taken and analyzed to verify and interpret these observations.

4. Summary and conclusions

The goals of this study were to characterize sources of OM in mangrove lagoon sediments and to evaluate changes in source contributions and C_{org} burial over time. It is imperative that source indicators clearly differentiate each type of OM input into the sedimentary pool. For example, if N and C isotopes had been utilized to determine OM source in these sediments, rather than the C isotopes and N/C ratios employed, the SPM contributions would not have been clearly recognized.

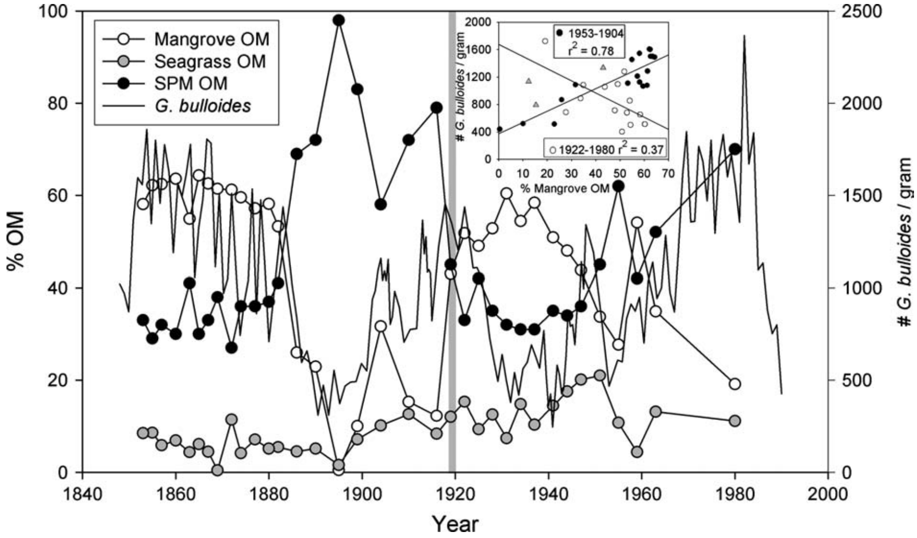


Fig. 5. Plot of station 9 Chelem % sedimentary OM source (mangroves are white circles, seagrasses are gray circles and black circles are SPM, all with connection lines) vs. abundances of *Globigerina bulloides* (black lines; Black et al., 1999). The phase relationship between these records is different before and after about 1920 (indicated by the vertical line). The inset graph shows the linear correlation between % mangrove OM and *G. bulloides* abundances (#/gram, 5 year running average), with a high correlation coefficient ($r^2 = 0.78$) from 1853 to 1904 (filled circles) and a lower one from 1922 to 1980 (empty circles, $r^2 = 0.37$).

Since SPM accounts for about 40% of sedimentary C_{org} at some sites, this is quite significant. In addition, it is evident from our results that the validity of the mixing models must be tested specifically for each location, since local environmental factors, such as post-depositional sedimentary biogeochemical processes and degree of anthropogenic influence, may affect the end member source signal. Mixing plots for Celestun and Chelem lagoons were largely applicable for the entire lagoon, likely due to the relative simplicity of OM inputs into the sediment and to the small size of these lagoons. In the case of Terminos, a much larger lagoon with more variability in natural and anthropogenic influences, end member OM sources at different stations had different $\delta^{13}C$ and N/C ratios. Such variability may complicate interpretations of OM source changes over time if the end member signals are susceptible to alteration. Mangrove, seagrass and SPM contributions to lagoon sediments varied between stations within each lagoon depending on the dominant vegetation at each site. Mangroves contribute 30–80% C_{org} in fringe mangrove sediments and 0–20% in mid-lagoon seagrass sites. The close coupling between local vegetation and OM burial suggests little transport and mixing of particulate OM throughout the lagoons.

OM source dynamics vary over time in each lagoon. Chelem and Terminos seem to be dominated by changes in the relative contributions from mangrove and SPM (constant seagrass contribution), while all three OM sources contribute to changes in the sedimentary C_{org} pool in Celestun Lagoon. In particular, Celestun has on average a greater seagrass contribution to sedimentary C_{org} than the other two lagoons. One potential explanation for this observation is that the seagrass community in Celestun Lagoon is healthier than in Chelem or Terminos, both of which experience a greater anthropogenic impact. The overall low seagrass C_{org} contributions in Chelem and Terminos implies that seagrasses contribute to C_{org} burial only in limited areas where conditions are optimal. Alternatively, these results may indicate that seagrass decomposition and regeneration is more effective in Chelem and Terminos. To evaluate which of the above explanations is more consistent with the data, a better estimate of the contribution of seagrasses to the net primary production at each site in all of the lagoons is needed, and such data is currently unavailable.

In each of the three lagoons, SPM contributes a large portion of C_{org} to the sediments, yet phytoplankton contribute only a minor fraction of total primary production. In Celestun (the only lagoon for which total primary production values are available), phytoplankton account for only 8% of total production (150 g C m^{-2} yr^{-1} out of 1860 g C m^{-2} yr^{-1} (Herrera-Silveira, 1994)), yet contribute 20–80% of sedimentary C_{org}, while mangroves account for 62% of total production (1460 g C m^{-2} yr^{-1}, personal communication from A. Zaldivar, 2002) and contribute a relatively smaller fraction of sedimentary C_{org} (20–70%). Seagrasses make up 30% of total production and about the same percentage of buried C_{org} in Celestun (Herrera-Silveira, 1994). Our results indicate that plankton-based primary production is an important, yet previously unappreciated, component of these ecosystems and contributes as much to long-term C storage as mangroves and seagrasses. Thus any preservation/protection measures to sustain such ecosystems should consider conservation of the entire ecosystem, including the health of phytoplankton and seagrass communities in addition to mangroves.

In this study, we show that in sediments with higher mangrove OM contribution, DW% C_{org} and DW% N_{total} are significantly higher than in sediments dominated by seagrass contribution (r^2 of <0.05 for both). This relation suggests that much of the C_{org} burial is concentrated within the fringe mangrove sites in these lagoons and thus C burial is enhanced in mangrove sediments. This is also highlighted by the higher rates of C_{org} burial in Celestun and Terminos lagoons compared with Chelem, where mangrove contributions to sedimentary OM are low at present, possibly as a result of human induced circulation changes (port construction) and other anthropogenic impacts. This may also suggest that mangrove sediments have less efficient nutrient regeneration than seagrass sediments (due to recalcitrant mangrove C_{org}) and thus seagrasses in these sites may be the source of nutrient export to the coast. Overall for these lagoons, average C_{org} burial is 53 g C m^{-2} yr^{-1}. The C_{org} burial rates reported in this study are lower than the average value reported for all mangrove ecosystems (100 g C m^{-2} yr^{-1}), although it is consistent with values for fringe mangroves in areas of low river discharge (see Fig. 5 in (Twilley et al., 1992)).

The observed decrease in rates of C_{org} burial, concurrent with a reduction in mangrove contributions to sedimentary OM in all three lagoons during the recent past, may suggest either that climatic fluctuations or anthropogenic perturbations negatively impact the mangrove ecosystem and reduce C_{org} burial. Such a trend is indeed more significant in Chelem and Terminos Lagoons than in the less impacted Celestun Lagoon, possibly highlighting the importance of anthropogenic disturbance to the health of these ecosystems. The reduction in C_{org} burial flux and contribution of mangroves to total C_{org} in fringe sediments relative to periods prior to about 1950 may however be driven by natural climatic variability, the affects of which are increased in areas under anthropogenic influence. Longer, higher resolution cores from these and other coastal lagoons are needed to clarify if the variability expressed in the core at station 9 in Chelem represents a regional trend. Given the observed correlation for at least part of the record between a deep-sea foraminiferal record and Chelem station 9 OM source, more and longer records from these lagoons may elucidate the climate-related variability which effects vegetation distribution and sedimentary processes in these lagoons. The temporal variability in C_{org} burial observed in these cores illustrates the need for further understanding of how these systems respond to natural change before the specific influence of anthropogenic impacts hypothesized here can be assessed.

Acknowledgements

We thank Dr. C. Kendall for allowing us to use her mass spectrometer for elemental and isotope analyses of sediment samples. We thank Dr. R. Ramesh and Dr. B. McKee for ^{210}Pb analyses. Sampling assistance was provided by M. Young, A. Zaldivar and J. Ramírez-Ramírez. This work was funded by NSF INT-Americas Program grant #0128178 to AP. M. Eagle Gonneea was supported by fellowships from the American Meteorological Society and the Wright Fund, Stanford University.

References

Alongi, D.M., 1996. The dynamics of benthic nutrient pools and fluxes in tropical mangrove forests. Journal of Marine Research 54, 123–148.

Andrews, J.E., Greenaway, A.M., Dennis, P.F., 1998. Combined carbon isotope and C/N ratios as indicators of source and fate of organic matter in a poorly flushed, tropical estuary: Hunts Bay, Kingston Harbour, Jamaica. Estuarine, Coastal and Shelf Science 46, 743–756.

Black, D.E., Peterson, L.C., Overpeck, J.T., Kaplan, A., Evans, N.N., Kashgarian, M., 1999. Eight centuries of North Atlantic Ocean atmosphere variability. Science 286, 1709–1713.

Bouillon, S., Mohan, P.C., Sreenivas, N., Dehairs, F., 2000. Sources of suspended organic matter and selective feeding by zooplankton in an estuarine mangrove ecosystem as traced by stable isotopes. Marine Ecology Progress Series 208, 79–92.

Chong, V.C., Low, C.B., Ichikawa, T., 2001. Contribution of mangrove detritus to juvenile prawn nutrition: A dual stable isotope study in a Malaysian mangrove forest. Marine Biology 138, 77–86.

Cifuentes, L.A., Coffin, R.B., Solorzano, L., Cardenas, W., Espinoza, J., Twilley, R.R., 1996. Isotopic and elemental variation of carbon and nitrogen in a mangrove estuary. Estuarine, Coastal and Shelf Science 43, 781–800.

Curtis, J.H., Hodell, D.A., Brenner, M., 1996. Climate variability on the Yucatan Peninsula (Mexico) during the past 3500 years, and implications for Maya cultural evolution. Quaternary Research 46 (1), 37–47.

Curtis, J.H., Brenner, M., Hodell, D.A., Balser, R.A., Islebe, G.A., Hooghiemstra, H., 1998. A multi-proxy study of Holocene environmental change in the Maya lowlands of Peten, Guatemala. Journal of Paleolimnology 19 (2), 115–128.

Day, J.W., Conner, W.H., Ley-Lou, F., Day, R.H., Navarro, A.M., 1987. The productivity and composition of mangrove forests, Laguna de Terminos, Mexico. Aquatic Botany 27, 267–284.

Day, J.W., Coronado-Molina, C., Vera-Herrera, F.R., Twilley, R., Rivera-Monroy, V.H., Alvarez-Guillen, H., Day, R.H., Conner, W.H., 1996. A 7 year record of above-ground net primary production in a southeastern Mexican mangrove forest. Aquatic Botany 55, 39–60.

de Boer, W., 2000. Biomass dynamics of seagrasses and the role of mangrove and seagrass vegetation as different nutrient sources for an intertidal ecosystem. Aquatic Botany 66, 225–239.

Dittmar, T., Lara, R.J., Kattner, G., 2001. River or mangrove? Tracing major organic matter sources in tropical Brazilian coastal waters. Marine Chemistry 73, 253–271.

Fleming, M., Lin, G., Sternberg, L.d.S.L., 1990. Influence of mangrove detritus in an estuarine ecosystem. Bulletin of Marine Science 47 (3), 663–669.

Fogel, M.F., Sprague, E.K., Gize, A.P., Frey, R.W., 1989. Diagenesis of organic matter in Georgia salt marshes. Estuarine, Coastal and Shelf Research 28, 211–230.

Fry, B., Sherr, E.B., 1984. δ^{13}C measurements as indicators of carbon flow in marine and freshwater ecosystems. Contributions to Marine Science 27, 13–47.

Graham, M.C., Eaves, M.A., Farmer, J.G., Dobson, J., Fallick, A.E., 2001. A study of carbon and nitrogen stable isotope and elemental ratios as potential indicators of source and fate of organic matter in sediments of the Forth Estuary, Scotland. Estuarine, Coastal and Shelf Science 52, 375–380.

Herrera-Silveira, J.A., 1994. Phytoplankton productivity and submerged macrophyte biomass variation in a tropical coastal lagoon with groundwater discharge. Vie Milieu 44 (3/4), 257–266.

Herrera-Silveira, J.A., 1996. Salinity and nutrients in a tropical coastal lagoon with groundwater discharges to the Gulf of Mexico. Hydrobiologia 321, 165–176.

Herrera-Silveira, J.A., Comín, F.A., 1995. Nutrient fluxes in a tropical coastal lagoon. Ophelia 42, 127–146.

Herrera-Silveira, J.A., Comín, F.A., López, S., Sáchez, I., 1998a. Limnological characterization of aquatic ecosystems in Yucatán Peninsula (SE México). Verhandlungen Internationale Vereinigung für Limnologie 26, 1348–1351.

Herrera-Silveira, J.A., Ramírez-Ramírez, J., Zaldivar, A.J., 1998b. Overview and characterization of the hydrology and primary producer communities of selected coastal lagoons of Yucatán, México. Aquatic Ecosytem Health and Management 1, 353–372.

Hodell, D.A., Curtis, J.H., Brenner, M., 1995. Possible role of climate in the collapse of Classic Maya civilization. Nature 375, 391–394.

Holmer, M., Olsen, A.B., 2002. Role of decomposition of mangrove and seagrass detritus in sediment carbon and nitrogen cycling in a tropical mangrove forest. Marine Ecology Progress Series 230, 87–101.

Jennerjahn, T.C., Ittekkot, V., 2002. Relevance of mangroves for the production and deposition of organic matter along tropical continental margins. Naturwissenschaften 89, 23–30.

Kaplan, I.R., Cline, R.M., 1979. Isotopic fractionation of dissolved nitrate during denitrification in the eastern tropical North Pacific Ocean. Marine Chemistry 3 (4), 271–299.

Kristensen, E., Holmer, M., Banta, G.T., Jensen, M.H., Hansen, K., 1995. Carbon, nitrogen and sulfur cycling in sediments of the Ao Nam Bor mangrove forest, Phuket, Thailand: A review. Phuket Marine Biological Center Research Bulletin 60, 37–64.

Lee, S.Y., 1995. Mangrove outwelling: a review. Hydrobiologia 295, 203–212.

Lee, S.Y., 2000. Carbon dynamics of Deep Bay, eastern Pearl River estuary, China. II: Trophic relationship based on carbon- and nitrogen-stable isotopes. Marine Ecology Progress Series 205, 1–10.

Loneragan, N.R., Bunn, S.E., Kellaway, D.M., 1997. Are mangroves and seagrasses sources of organic carbon for penaeid prawns in a tropical Australian estuary? A multiple stable-isotope study. Marine Biology 130, 289–300.

Lynch, J.C., Meriwether, J.R., McKee, B.A., Vera-Herrera, F., Twilley, R.R., 1989. Recent accretion in mangrove ecosytems based on ^{137}Cs and ^{210}Pb. Estuaries 12 (4), 284–299.

Macko, S.A., Engel, M.H., Parker, P.L., 1993. Early diagenesis of organic matter in sediments: assessment of mechanisms and preservation by the use of isotopic molecular approaches. In: Engel, M.H., Macko, S.A. (Eds.), Organic Geochemistry: Principles and Applications. Topics in Geobiology. Plenum Press, New York, pp. 211–224.

Mariotti, A., Germon, J.C., Hubert, P., Kaiser, P., Letolle, R., Tardieux, A., Tardieux, P., 1981. Experimental determination of nitrogen kinetic isotope fractionation: some principles; illustration for the denitrification and nitrification processes. Plant Soil 62, 413–430.

Matson, E.A., Brinson, M.M., 1990. Stable carbon isotopes and the C:N ratio in the estuaries of the Pamlico and Neuse Rivers, North Carolina. Limnology and Oceanography 35 (6), 1290–1300.

Meyers, P.A., Ishiwatari, R., 1993. The early diagenesis of organic matter in lacustrine sediments. In: Engel, M.H., Macko, S.A. (Eds.), Organic Geochemistry: Principles and Applications. Geobiology. Plenum, New York, pp. 185–209.

Middleburg, J.J., Nieuwenhuize, J., 1998. Carbon and nitrogen stable isotopes in suspended matter and sediments from the Schelde Estuary. Marine Chemistry 60, 217–225.

Newell, R.I.E., Marshall, N., Sasekumar, A., Chong, V.C., 1995. Relative importance of benthic microalgae, phytoplankton, and mangroves as sources of nutrition for penaeid prawns and other coastal invertebrates from Malaysia. Marine Biology 123, 595–606.

Rivera-Monroy, V.H., Twilley, R.R., 1996. The relative role of denitrification and immobilization in the fate of inorganic nitrogen in mangrove sediments (Terminos Lagoon, Mexico). Limnology and Oceanography 41 (2), 284–296.

Rogers, K.M., 1999. Effects of sewage contamination on macro-algae and shellfish at Moa Point, New Zealand using stable carbon and nitrogen isotopes. New Zealand Journal of Marine and Freshwater Research 33, 181–188.

Schultz, D.J., Calder, J.A., 1976. Organic carbon ^{13}C/^{12}C variations in estuarine sediments. Geochimica et Cosmochimica Acta 40, 381–385.

Spies, R., Kruger, H., Ireland, R., Rice Jr., D.W., 1989. Stable isotope ratios and contaminant concentrations in a sewage-distorted foodweb. Marine Ecology Progress Series 54, 157–170.

Thornton, S.F., McManus, J., 1994. Application of organic carbon and nitrogen stable isotopes and C/N ratios as source indicators of organic matter provenance in estuarine systems: Evidence from the Tay Estuary, Scotland. Estuarine, Coastal and Shelf Science 38, 219–233.

Twilley, R., Chen, R.H., Hargis, T., 1992. Carbon sinks in mangroves and their implications to carbon budget of tropical coastal ecosystems. Water, Air and Soil Pollution 64 (1–2), 265–288.

Valdes, D.S., Real, E., 1998. Variations and relationships of salinity, nutrients and suspended solids in Chelem coastal lagoon at Yucatan, Mexico. Indian Journal of Marine Science 27, 149–156.

Valiela, I., Cole, M.L., 2002. Comparative evidence that salt marshes and mangroves may protect seagrass meadows from land-derived nitrogen loads. Ecosystems 5, 92–102.

Valiela, I., Bowen, J.L., York, J.K., 2001. Mangrove forests: one of the world's threatened major tropical environments. BioScience 51 (10), 807–815.

Woodroffe, C., 1992. Mangrove sediments and geomorphology. In: Robertson, A.I., Alongi, D.M. (Eds.), Tropical Mangrove Ecosystems. American Geophysical Union, Washington, DC, pp. 7–41.

Yamamuro, M., 2000. Chemical tracers of sediment organic matter origins in two coastal lagoons. Journal of Marine Systems 26, 127–134.

Yamamuro, M., Kayanne, H., 1995. Rapid direct determination of organic carbon and nitrogen in carbonate-bearing sediments with a Yanaco MT-5 CHN analyzer. Limnology and Oceanography 40 (5), 1001–1005.