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Stable Carbon Isotope Signatures of Sedimentary Carbon in Coastal Wetlands as Indicators of Salinity Regime

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ABSTRACT

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Stable carbon isotope values of organic carbon have proven useful in identification of the salinity regime of marsh deposits in the Mississippi Delta plain. Using a mixing model and empirical measurements of the $\delta^{13}C$ of marsh sediments, we show that carbon isotope analysis could be a useful technique on other coastlines. Estimates of the stable carbon isotope values from estuarine deposits along the west and east coast of the United States suggest that fresh and saline sediments each have a characteristic "signature." Thus, stable carbon isotope values can provide valuable evidence of sea level fluctuations in these regions. Values of $\delta^{13}C$ which depart from the predictive model could be caused by diagenetic processes (decomposition) and/or contribution from carbon sources not accounted for in the model. In assessing the relative importance of these factors, we find that complications are minimized when autochthonous carbon from algal production is not an important component of the sedimentary organic matter.

ADDITIONAL INDEX WORDS: *Basal peat, paleo-salinity, sea level, estuarine marsh, salt marsh.*

INTRODUCTION

The origin of buried deposits from coastal wetlands is commonly interpreted from the stratigraphy of associated deposits (*e.g.*, KOSTERS, 1989), and analysis of macro-fossils (NIERING and WARREN, 1980), pollen (*e.g.*, MUDIE and BYRNE, 1980; CLARK and PATTERSON, 1985), or other microfossils (*e.g.*, SCOTT and MEDIOLI, 1986). In a study of sediments from the continental shelf of the northeastern United States EMERY *et al.* (1967) suggested that measurement of $\delta^{13}C$ would also be a useful means of distinguishing between ancient salt marsh and freshwater peat. They analyzed a number of peat samples, dated as old as 13,500 ± 350 B.P., which were determined to be of freshwater origin by pollen and diatom analyses. These freshwater peat samples had $\delta^{13}C$ values between -23.5 and -27.8‰ and were distinctly different from those measured in modern salt marsh sediments collected around Cape Cod, Massachusetts, which had $\delta^{13}C$ values of -11.6 to -15.5‰. EMERY *et al.* (1967), however, did not report any $\delta^{13}C$ values for ancient salt marsh peat, and there seems to have been little immediate interest in pursuing the possibilities for stable carbon isotope analyses as an aid in peat stratigraphy.

The lack of immediate interest in $\delta^{13}C$ studies may be due in part to the lack of understanding of the mechanisms causing the difference in $\delta^{13}C$ values. No explanation was available for these differences in peat until SMITH and EPSTEIN (1971) reported that differences in photosynthetic pathways resulted in different degrees of fractionation of atmospheric CO_2 in land plants. These two groups of plants, termed C-3 and C-4 plants, have distinct $\delta^{13}C$ ranges from -23 to -34‰ and -9 to -17‰, respectively.

The C-4 plants have an additional photosynthetic pathway, the Hatch-Slack pathway, which is associated with adaptations to avoid drought stress. Plants with the Hatch-Slack pathway, in-

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cluding CAM (Crassulacean acid metabolism) plants, have an obvious advantage not only in desert environments, but also in salt marshes where high salt concentrations in soil water cause drought stress for higher plants. In the salt marshes of temperate to sub-tropical North America, the majority of flowering plants are C-4 or CAM plants, producing carbon within the higher range (less negative) of $\delta^{13}C$ values. Fresh water marshes are generally dominated by C-3 plant species. In estuarine wetlands, there may be a gradual transition from a C-3—dominated plant community to a C-4—dominated plant community, paralleling the salinity gradient. In coastal wetlands of Louisiana CHMURA *et al.* (1985 and 1987) demonstrated that the $\delta^{13}C$ of carbon in surface sediments along a salinity gradient can be predicted using a mixing model which considers relative abundances of C-3 and C-4 plants. Applicability of stable carbon isotope values in identification of changes in salinity of subsurface deposits in Louisiana has been demonstrated by DELAUNE (1986) and CHMURA *et al.* (1987).

In this paper, we predict stable carbon isotope values for sediments in typical estuaries of the west and east coasts of North America, showing fresh and saline deposits have isotope "signatures" in these regions as well. Processes which could cause variability in empirical measurements are also considered. Our mixing model can be applied to plant communities not covered in this paper because, we provide a compilation of published $\delta^{13}C$ values of carbon from a variety of plant species or genera recognized as components of wetland vegetation.

In studies of Quaternary coastal deposits, it is often desirable to determine the date of initial intrusion of seawater into a basin. Carbon dating of the basal peat deposit is now often performed using the AMS (accelerator mass spectrometer) method, which can readily provide a measurement of $\delta^{13}C$ abundance. Armed with knowledge of the $\delta^{13}C$ "signature" of regional fresh and salt marsh sediments, the coastal stratigrapher then has easily accessible evidence available to verify the origin of the basal peat.

METHODS

Where possible we use empirical values for the $\delta^{13}C$ of sedimentary carbon. In most cases these values are obtained from published studies in which the objective was for some purpose unrelated to peat stratigraphy, such as food web tracing, production of biomass, etc. When empirical values are not available, they are estimated based on published descriptions of the vegetation of the wetlands of the region. In selecting these publications, we searched for descriptions which included details on vegetation cover or biomass estimates by individual species. The estimates of biomass were used to apply the mixing model described by CHMURA *et al.* (1987) for prediction of the $\delta^{13}C$ of sedimentary carbon. This model is based on the assumption that sources of sediment carbon are primarily autochthonous, from vascular plants, and contributed in direct proportion to the above ground biomass of each species present:

$$\delta^{13}C_{\mathrm{sediment}_i} = \frac{\sum_{n=1}^{i} (\%\ \mathrm{biomass}_i)(\delta^{13}C)}{\sum_{n=1}^{i} (\%\ \mathrm{biomass}_i)}$$

Where i = each species found in the wetland community.

The $\delta^{13}C$ values for sediment carbon taken from published reports are noted in the text and figures. All $\delta^{13}C$ values for plant species are based on whole plant tissue and are provided in Table 1. Where possible we used $\delta^{13}C$ values for the individual species, although some authors have made identifications simply to genus. In this case entries are simply listed as genus values. For those species for which no value could be obtained, the range reported for its genus is substituted.

Some of our own unpublished values are also used, obtained with methodologies detailed in CHMURA *et al.* (1987). Our bulk sediment or plant samples were treated with HCl to remove carbonates, dried and ground to powder. After samples were combusted, CO_2 gas was separated through cryogenic distillation and analyzed on a mass spectrometer. Our results and all other stable carbon isotope values used in this paper are reported in conventional delta (δ) notation in per mil (‰) relative to the international standard PDB according to CRAIG (1957). The $\delta^{13}C$ notation expresses the $^{13}C/^{12}C$ ratio as defined by the equation:

$$\delta^{13}C = [(^{13}C/^{12}C_{\mathrm{sample}}/^{13}C/^{12}C_{\mathrm{standard}}) - 1] \times 10^3.$$

REGIONAL SIGNATURES

Northeastern Estuaries

The potential for distinctive $\delta^{13}C$ signatures here is high; composition of vegetation communities

Table 1. *List of reported $\delta^{13}C$ values (‰, PDB) of whole tissue from vascular plant species or genera known to grow in wetland environments.*

			$\delta^{13}C$, PDB (‰)		
Family	Genus	Species	Max	Min	Reference*
Alismataceae	*Sagittaria*	sp.	−25.7		1
Amaranthaceae	*Alternanthera*	*philoxeroides*	−28.4	−29.3	7, 21
Batidaceae	*Batis*	*maritima*	−26.7	−26.7	20
Chenopodiaceae	*Atriplex*	*patula*	−25.0	−27.8	21
Chenopodiaceae	*Salicornia*	sp.	−25.1		14
Chenopodiaceae	*Salicornia*	*bigelovii*	−24.7	−25.2	20
Chenopodiaceae	*Salicornia*	*virginica*	−26.0		11
Chenopodiaceae	*Sueda*	*fructicosa*	−26.5		19
Chenopodiaceae	*Halimione*	*portulacoedes*	−26.3		14
Compositae	*Borrichia*	*frutescens*	−26.0		11
Cyperaceae	*Carex*	sp.	−11.5	−25.0	20
Cyperaceae	*Cladium*	*jamaicense*	−26.2		5, 21
Cyperaceae	*Cyperus*	*odoratus*	−12.1		21
Cyperaceae	*Cyperus*	*eragraostis*	−12.8		21
Cyperaceae	*Cyperus*	*rotundus*	−13.7		21
Cyperaceae	*Cyperus*	*eustalatus*	−12.1		21
Cyperaceae	*Cyperus*	*pectinatus*	−26.0		8
Cyperaceae	*Eleocharis*	sp.	−19.7		5
Cyperaceae	*Eleocharis*	*dulcis*	−26.0		8
Cyperaceae	*Fuirena*	*stricta*	−27.1		8
Cyperaceae	*Pycreus*	*nitidus*	−11.9		8
Cyperaceae	*Scirpus*	sp.	−27.0		6
Cyperaceae	*Scirpus*	*americanus*	−26.0		13
Cyperaceae	*Scirpus*	*ecustris*	−28.7		21
Cyperaceae	*Scirpus*	*cernuus*	−30.5		21
Gramineae	*Distichlis*	*spicata*	−12.8	−14.7	4, 5, 20
Gramineae	*Echinochloa*	*crus galli*	−16.2		21
Gramineae	*Echinochloa*	*frumentacea*	−15.2		21
Gramineae	*Frankenia*	*grandifolia*	−26.4		19
Gramineae	*Imperata*	*cylindrica*	−12.8		8
Gramineae	*Leersia*	*oryzoides*	−27.5		18
Gramineae	*Miscanthus*	*capensis*	−12.3		8
Gramineae	*Monanthochloe*	*littoralis*	−15.3		19
Gramineae	*Panicum*	*dichotoflorum*	−14.1		18
Gramineae	*Panicum*	*hemitomon*	−25.2	−27.5	1, 18
Gramineae	*Panicum*	*repens*	−11.4		18
Gramineae	*Paspalum*	*vaginatum*	−11.3		18
Gramineae	*Paspalum*	*distichum*	−12.9		21
Gramineae	*Paspalum*	*notatum*	−12.1		21
Gramineae	*Phragmites*	*australis*	−24.6	−29.4	6, 18, 21
Gramineae	*Puccinellia*	*maritima*	−23.3		14
Gramineae	*Sacciolepis*	*indica*	−10.9	−27.1	7, 18
Gramineae	*Setaria*	*italica*	−14.4		21
Gramineae	*Setaria*	*sphacelata*	−13.9		21
Gramineae	*Setaria*	*viridis*	−13.4		21
Gramineae	*Spartina*	*alterniflora*	−12.1	−15.5	2, 3, 11, 16, 17
Gramineae	*Spartina*	*patens*	−11.7	−13.6	1, 9
Gramineae	*Spartina*	*anglica*	−13.6		14
Gramineae	*Spartina*	*cynosuroides*	−12.0	−13.6	5, 10, 12
Gramineae	*Sporobolus*	*virginicus*	−13.3		11
Gramineae	*Zizania*	*aquatica*	−25.5		18
Gramineae	*Zizaniaopsis*	*miliacea*	−26.1		18
Holoragaceae	*Myriophyllum*	*spicatum*	−16.3		5
Hydrocharitaceae	*Thalassia*	*testudium*	−11.4		16
Juncaceae	*Juncus*	*roemerianus*	−22.8	−26.0	5, 10, 11, 14, 15
Lemnaceae	*Lemna*	*minor*	−33.6		21
Lemnaceae	*Spirodela*	*polyrhiza*	−27.5		1
Onagraceae	*Ludwigia*	*leptocarpa*	−26.1		8

Table 1. *Continued.*

Family	Genus	Species	$\delta^{13}C$, PDB (‰) Max	Min	Reference*
Moraceae	*Ficus*	*verruculosa*	−26.8		8
Nymphaceae	*Nyphaea*	*caerulea*	−22.3		8
Plumbaginaceae	*Limonium*	*commune*	−23.2		19
Polygonaceae	*Polygonum*	*hydropiper*	−29.8		7
Polypodiaceae	*Thelypteris*	*confluens*	−28.2		8
Pontedariaceae	*Eichhornia*	sp.	−31.8		20
Portulaceae	*Mesembryanthemum*	*chilense*	−23.6		19
Potamogetonaceae	*Halodule*	*wrightii*	−13.9	−10.2	16
Potamogetonaceae	*Syringodium*	*filiforme*	−10.0		16
Saccarinae	*Eriochrysis*	*pallida*	−12.6		8
Sphagnaceae	*Sphagnum*	*magellanicum*	−26.0		20
Typhaceae	*Typha*	sp.	−27.6		20
Typhaceae	*Typha*	*angustifolia*	−25.2		6
Typhaceae	*Typha*	*capensis*	−28.1		8
Zosteraceae	*Phyllospadix*	*torreyi*	−14.0		19
Zosteraceae	*Ruppia*	*maritima*	−11.1	−14.7	5, 16
Zosteraceae	*Zostera*	*marina*	−10.0		19

* References: 1) this study; 2) ALBERTS *et al.*, 1988; 3) BENNER *et al.*, 1987; 4) BJORKMAN and GAUHL, 1969; 5) CRAFT *et al.*, 1988; 6) DENIRO and HASTORF, 1985; 7) EHLERINGER *et al.*, 1987; 8) ELLERY *et al.*, 1992; 9) EMERY *et al.*, 1967; 10) HACKNEY and HAINES, 1980; 11) HAINES, 1976; 12) HAINES and MONTAGUE, 1979; 13) HUGHES and SHERR, 1983; 14) JACKSON *et al.*, 1986; 15) JOHNSON and CALDER, 1973; 16) SACKETT, 1986; 17) SCHWINGHAMER *et al.*, 1983; 18) SMITH and BROWN, 1973; 19) SMITH and EPSTEIN, 1970; 20) SMITH and EPSTEIN, 1971; 21) TROUGHTON *et al.*, 1974

suggests that there would be a progressive depletion in ^{13}C from the low marsh (flooded by daily tides) to high salt marsh (higher in elevation and thus flooded less frequently) through the brackish wetlands and into fresh marshes (Figure 1). On the northeast coast of North America, the low marsh is nearly a mono-specific stand of *Spartina alterniflora,* a C-4 plant (TEAL, 1986). The occasional *Salicornia* or other forb (non-grassy herb) adds little in terms of plant biomass. The $\delta^{13}C$ value of low marsh sedimentary organic matter, −15.5‰, was empirically determined from a sediment sample collected by CHMURA (1982) for studies of estuarine marsh sediments of the Palmer River on the Rhode Island/Massachusetts border. NIXON (1982) describes the northeastern high marsh zone. Its vegetation is dominated by the C-4 species *Spartina patens* and *Distichlis spicata,* as well as *Juncus gerardi,* a C-3 species. Our predictions of more ^{13}C-depleted values in the high marsh sediments are supported by the measurement of −17.8‰ at the Palmer River site. In this region there is often a transition from salt marsh to *Phragmites autralis* (=*communis*) under brackish conditions. Our measurements show that sedimentary organic matter in this zone is even further depleted (−23.4‰), but not to the extent expected in fresh water wetlands such as *Typha* (cattail) marshes common in this region.

The composition of vegetation communities of "northeastern" marshes is consistent as far south as Chesapeake Bay (REIMOLD, 1977). Thus, the $\delta^{13}C$ values of sedimentary organic matter on the northeast coast may be applied this far south. Although *Spartina alterniflora*-dominated low marsh is characteristic of salt marshes as far north as Newfoundland (REIMOLD, 1977), vegetation of the high marsh begins to vary at the Bay of Fundy. There, the high marsh includes a greater proportion of forbs such as *Plantago maritima* and *Triglochin elata* which may be locally dominant. To date we have found no reports of $\delta^{13}C$ values of these plants; at this stage, predictions regarding the sedimentary organic matter would be unwarranted.

Southeastern Estuaries

Reviews of regional coastal vegetation ecology can be found in COPELAND *et al.* (1984a and 1984b). As in the northeast there is expected to be a gradual shift of $\delta^{13}C$ values from low marsh to brackish fringe (Figure 2). *Spartina alterniflora* contributed most of the carbon to sediments of a Georgia low marsh studied by FOGEL *et al.* (1989), but the values of −18 to −19‰ are more depleted than that measured in low salt marsh to the north. CRAFT *et al.* (1988) measured the $\delta^{13}C$ of sedimentary organic matter in salt marshes of North

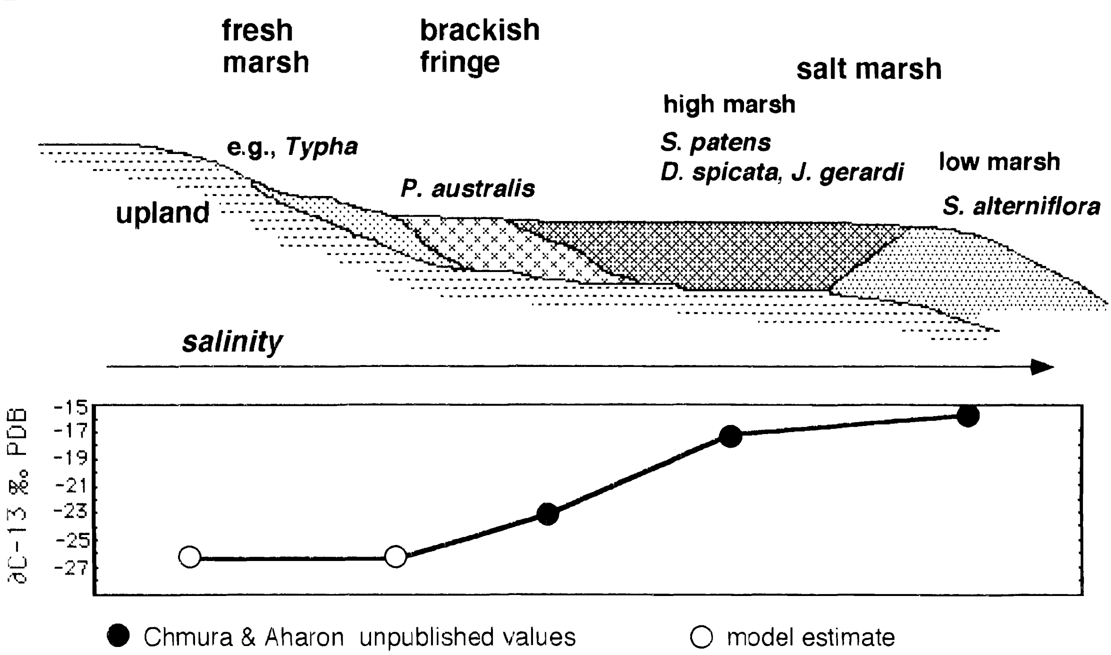

Figure 1. Generalized cross section depicting marsh plant communities and the corresponding predicted or empirical values of $\delta^{13}C$ in sedimentary organic matter along a typical estuarine salinity gradient along the northeastern coast (from Chesapeake Bay to Bay of Fundy) of North America. Calculation of $\delta^{13}C$ values is explained in text.

Carolina. In the high marsh zones, characterized by *Spartina patens* and *Distichlis spicata*, they reported a $\delta^{13}C$ of −19.7‰, also somewhat more depleted than high marsh sediment to the north. Values of $\delta^{13}C$ in brackish wetland sediments in the southeast could be more variable. While sedimentary organic matter in zones dominated by *Spartina cynosuroides* had $\delta^{13}C$ values of −21.2‰ (CRAFT *et al.*, 1988), sediments of the *Juncus roemerianus* community could be even more depleted. Vegetation of fresh marshes in this region may be dominated by C-3 plants (ODUM *et al.*, 1984), and also be expected to have a depleted $\delta^{13}C$ (−27.6‰). A complication, however, would be created by the presence of *Spartina cynosuroides*, a C-4 plant which can be important in fresh as well as brackish marshes of this region. Using our mixing model we predict that values could be as enriched as those in the high marsh (−17‰). Thus, ^{13}C-depleted sedimentary organic matter could be confidently interpreted as fresh water or terrestrial/upland deposits, but in the southeast enriched values must be qualified by secondary evidence.

Southern California Estuary

The most tentative signatures are those proposed for marshes along the coast of southern California. Dominant species include CAM plants, such as *Salicornia* (ZEDLER, 1982), which tend to have more variable $\delta^{13}C$ values. The prevalence of *Salicornia* is due to the combined atmospheric aridity and high evapotranspiration which can cause hypersaline condition over much of the upper marsh (ZEDLER, 1982). An additional consequence of these conditions is sparser cover of flowering plants, which allows greater surface area for algal growth. Large contributions of carbon by benthic salt marsh algae could shift $\delta^{13}C$ values of sedimentary organic matter in this region, but there is not enough information yet available to make any estimates of the magnitude or direction of the shift. Hence, our estimates consider only inputs from carbon of higher plants.

The California estuary supports different species from those found on the Atlantic coast, but the transitions in plant communities are similar in terms of C-4 versus C-3 compositions (Figure

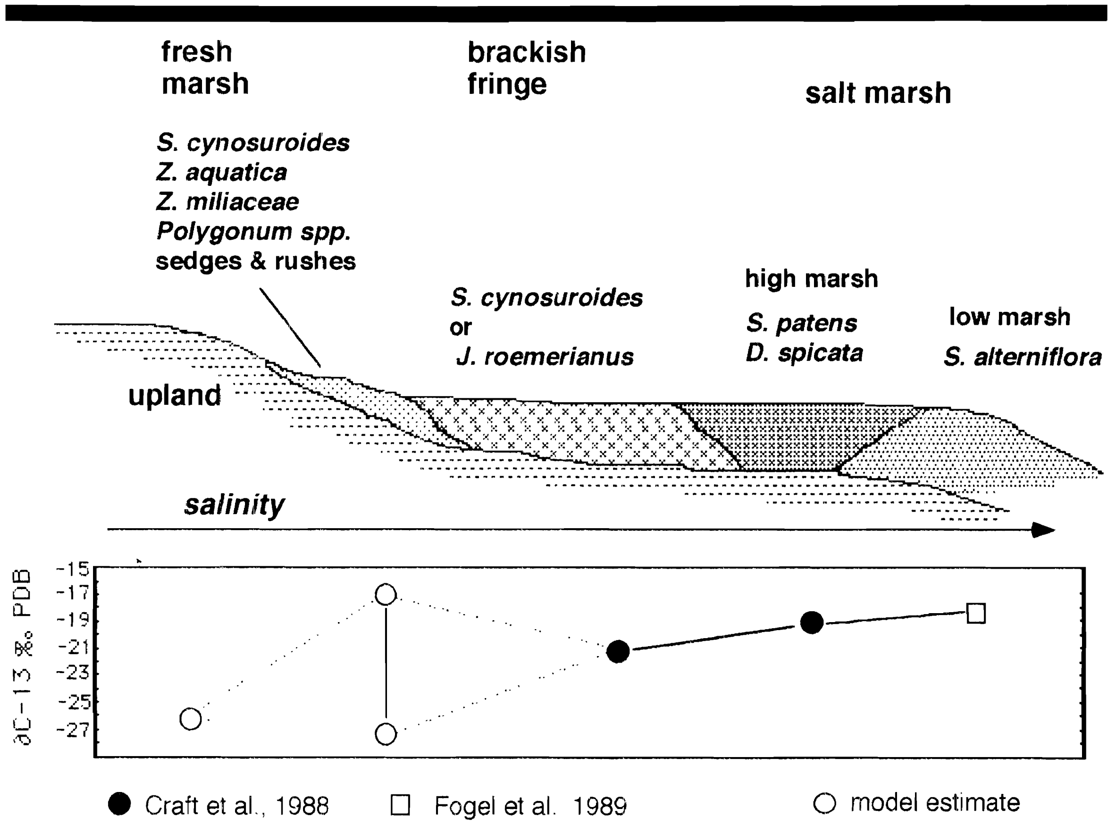

Figure 2. Generalized cross section depicting marsh plant communities and the corresponding predicted or empirical values of δ^{13}C in sedimentary organic matter along a typical estuarine salinity gradient along the southeastern coast (from Chesapeake Bay south to sub-tropical mangroves) of North America. Calculation of δ^{13}C values is explained in text.

3). We have not located studies of the δ^{13}C of marsh sedimentary organic matter for this region, thus signatures are based solely on model predictions. ZEDLER (1982) has reviewed the vegetation ecology of southern California coastal wetlands. *Spartina foliosa,* a C-4 plant, dominates the lower marsh; thus, we expect the most enriched δ^{13}C values in the sedimentary organic matter of this zone. As in other regions, C-3 plants are generally dominant in fresh marsh and terrestrial/upland communities. The most depleted δ^{13}C values would be expected in these deposits. Between the *Spartina foliosa* zone and the fresh marsh, our model estimates a gradual shift from sedimentary organic matter enriched in δ^{13}C to depleted values of the fresh marsh. In brackish marshes one would expect to find *Juncus acuta,* for which we have not found δ^{13}C measurements. We base our estimated sedimentary organic matter values on measurements of *Juncus roemarianus,* but recognize that the δ^{13}C of the carbon of the two plants might significantly differ.

SOURCES OF δ^{13}C VARIABILITY IN SEDIMENTARY ORGANIC MATTER

Decomposition of Plant Material

We would expect a negative shift in the δ^{13}C of sedimentary organic matter through decomposition, due to the variation in δ^{13}C of the chemical components of plant tissues. As decomposition proceeds, the most labile compounds, isotopically heavy relative to whole plant tissue, are lost first (BENNER *et al.,* 1987; EMBER *et al.,* 1987). Lignin, the most refractory compound, occurs only in woody and herbaceous plants (*e.g.,* not algae) and is generally depleted in ^{13}C by 2 to 6‰ relative to whole plant tissue. A negative shift in the δ^{13}C does seem to occur rapidly after deposition. CHMURA *et al.* (1987) found that δ^{13}C values of

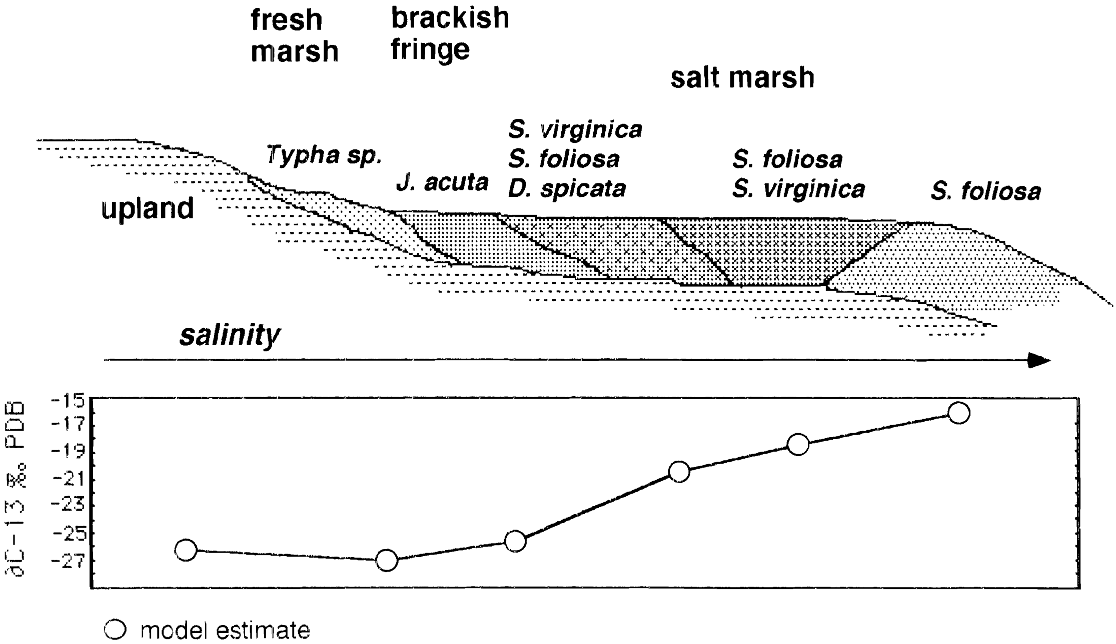

Figure 3. Generalized cross section depicting marsh plant communities and the corresponding predicted or empirical values of $\delta^{13}C$ in sedimentary organic matter along a typical estuarine salinity gradient along the southern California coast of North America. Calculation of $\delta^{13}C$ values is explained in text.

sedimentary organic matter were depleted by as much as 4‰ from the expected value of the whole plant carbon. In a study of diagenesis of organic matter in a Georgia salt marsh FOGEL *et al.* (1989) also found sedimentary organic matter depleted with respect to the *S. alterniflora* source carbon, but reported that $\delta^{13}C$ values were remarkably constant from the surface muds to depths of 150 cm (estimated to be 1400 yr). CHMURA (1990) found that in sediments as old as 2,000 yr B.P. the $\delta^{13}C$ of sedimentary organic matter generally corresponded to the original carbon source, as determined by pollen analysis. It is important to note that these studies analyzed bulk sediments and not extracts of humic acids or various plant compounds. The $\delta^{13}C$ of bulk sediments seems to integrate the remnants of plant carbon and the products of diagenesis, and under anaerobic conditions, it remains relatively stable after initial deposition.

Carbon Sources

Allochthonous Carbon Sources

Particulate and dissolved carbon may be transported to wetlands in fluvial and tidal floodwaters. As the majority of terrestrial (upland) species are C-3, the $\delta^{13}C$ of this carbon source would be depleted with respect to the vascular plants of salt marshes, but within the range of the autochthonous sources within freshwater marshes. Extensive deposition of carbon from upland terrestrial environments would act to mask the $\delta^{13}C$ of the salt marsh plant community but would probably do little to change the $\delta^{13}C$ signature of freshwater peat.

The $\delta^{13}C$ of organic carbon in marine sediments, generally considered to range from −19 to −21‰ (SACKETT and THOMPSON, 1963), is intermediate to that measured in salt- and fresh marsh sediments. Input of marine sedimentary organic carbon to salt marsh sediments would be expected to cause a negative shift of its $\delta^{13}C$ value and a positive shift in freshwater sediments. In freshwater environments deposition of marine carbon would also be accompanied by influx of saltwater. If continual, this influx would have a devastating effect on the plants adapted to freshwater environs. Such episodes would be expected to occur in transgressive situations. Thus, an enrichment of ^{13}C through introduction of marine carbon would probably not cause significant misinterpretations of fresh marsh deposits by the peat stratigrapher.

Autochthonous carbon

The vascular plants, primarily grasses and sedges, of coastal wetlands are obvious contributors to sedimentary organic carbon and relatively easy to account for. Edaphic algae also provide a significant and more problematic source of sedimentary organic carbon. Salt marsh surfaces may support a diverse assortment of algal species, including: mats of benthic diatoms; green, yellow-green, blue-green, and even brown algae on exposed surfaces, entangled amongst grass stems, or as epiphytes on the stems of the vascular plants (TAYLOR, 1962). SULLIVAN and MONCREIFF (1990), reviewing the importance of edaphic algae to carbon production in estuaries, report that the ratio of net annual aerial production of edaphic algal to that of vascular plants typically ranges from 8 to 33% in coastal salt marshes of the Atlantic and Gulf coasts of the U.S.A. The algal carbon, however, has been found to constitute as much as 61% of the annual production in *Scirpus olnei* marshes of the Mississippi coast (SULLIVAN and MONCREIFF, 1990) and 76 to 140% in some California marshes (ZEDLER, 1980). In a study of the $\delta^{13}C$ of edaphic algae, SULLIVAN and MONCREIFF (1990) found values intermediate between the C-4 grass *Spartina alterniflora* and C-3 rush *Juncus roemerianus* (Tables 1 and 2). In general it seems that algal carbon would decrease the $\delta^{13}C$ of sedimentary organic carbon, particularly in salt marshes and could be partly responsible for the depletion of ^{13}C noted in these sediments. A study of plant compounds in Georgia salt marsh sediments could account for only 70% of total sedimentary organic carbon and humic substances as originating from decayed *Spartina alterniflora* (FOGEL *et al.*, 1989). The algal carbon source, however, contains less refractory compounds (RAVEN *et al.*, 1981) and is produced on the sediment surface; hence, it probably decomposes fairly readily, and in many regions is likely to contribute more to marsh food-webs than to sedimentary carbon. In contrast, the graminoids which are commonly abundant in marshes may produce as much carbon below ground, contributing lignin-rich carbon directly to sedimentary organic carbon.

Much of the discussion of carbon production in wetlands concentrates on that produced by the above ground portion of the plant. The number of studies of below ground production are more limited due to sampling difficulties, but clearly show that most of the dominant wetland plant species produce more carbon in their roots and rhizomes than in their leaves and stems (GOOD *et al.*, 1982). This is primarily a characteristic of the grasses, sedges, and rushes which have high root to shoot biomass ratios and are perennial. Annual plants characteristically allocate greater production to the above ground portion; thus, many non-graminoid herbaceous plants have minimal below ground production.

Studies of ^{13}C abundances in plant carbon have found little difference in the $\delta^{13}C$ of above and below ground portions of plants (*e.g.*, FOGEL *et al.*, 1989). Thus, the high below ground productivity in marshes is probably the greatest factor contributing to the expression of $\delta^{13}C$ signatures characteristic of the vascular plant community, rather than associated algal production or deposition of allochthonous carbon.

Spatial Variation in $\delta^{13}C$ Values of Plant Carbon

Uptake of CO_2 from the atmosphere by plants involves a significant kinetic isotope fractionation and $^{12}CO_2$ is preferentially utilized during photosynthesis (VOGEL, 1980; O'LEARY, 1981). Plants with the Hatch-Slack pathway (C-4 and CAM) are more efficient at fixing CO_2, trap a greater proportion of $^{13}CO_2$ relative to C-3 plants, and are thus more enriched in the heavier isotope.

Variations in the $\delta^{13}C$ of atmospheric carbon are reflected in the $\delta^{13}C$ of plant carbon, but there seems to be only minor systematic latitudinal variation in the $\delta^{13}C$ of atmospheric CO_2. Local variations in atmospheric $\delta^{13}C$, largely controlled by plant respiration, are probably more important (HOEFS, 1980). Thus, the $\delta^{13}C$ of most species is consistent over wide geographic areas. One of the most commonly mentioned (in terms of isotope ratios) wetland species is *Spartina alterniflora*. The $\delta^{13}C$ of carbon has been measured from specimens collected from the Gulf of Mexico (DELAUNE, 1986) to the Bay of Fundy (SCHWINGHAMER *et al.*, 1983), and the range of $\delta^{13}C$ is no more than 3.4‰ (Table 1).

Local variations in abundances of $^{13}CO_2$ appear to be more significant than geographic variation. Sampling within tropical flood plain forests along the Amazon River has shown that recycling of CO_2 within the plant community results in a systematic variation of $\delta^{13}C$ within plant carbon down river (MARTINELLI *et al.*, 1991). Recycling of atmospheric CO_2 has not been reported in herba-

Table 2. *List of reported $\delta^{13}C$ values (‰, PDB) of whole tissue from algae.*

Family	Genus	Species	$\delta^{13}C$, PDB, ‰		Reference*
			Max	Min	
		Macroalgae			
Chlorophyceae	*Codium*	*fragile*	−24.5		2
Corallinaceae	*Bossea*	sp.	−14.8		1
Corallinaceae	*Corallina*	*chilense*	−18.6		6
Fucaceae	*Acrocarpia*	*paniculata*	−21.1		2
Fucaceae	*Ascophyllum*	*nodosum*	−17.0		1
Fucaceae	*Cystophora*	*moniliformis*	−14.6		2
Fucaceae	*Fucus*	*vesiculosus*	−12.2	−17.6	1, 4, 5
Gelidiaceae	*Gelidium*	*robustum*	−25.5		1
Gigartinaceae	*Chondrus*	*crispus*	−24.4		1
Gigartinaceae	*Gigartina*	*cristata*	−20.2		6
Gigartinaceae	*Gigartina*	sp.	−20.6		2
Grateloupiaceae	*Grateloupia*	*setchellii*	−22.7		6
Laminariaceae	*Laminaria*	sp.	−28.4		1
Laminariaceae	*Laminaria*	*agardhii*	−15.8		1
Lessoniaceae	*Lessonia*	*corrugata*	−16.9		2
Lessoniaceae	*Macrocystis*	sp.	−18.0	−19.0	1
Lessoniaceae	*Macrocystis*	*pyrifera*	−17.5		6
Rhodomelaceae	*Bostrichia*	*radicans*	−18.4	−26.2	7
Rhodomelaceae	*Chondria*	*tenuissima*	−17.2		1
Rhodomelaceae	*Jeanerrettia*	sp.	−27.8		2
Rhodomelaceae	*Polysiphonia*	*nigrescens*	−17.1		1
Rhodophyceae	*Plocamium*	*angustum*	−30.9		2
Rhodymeniaceae	*Rhodymenia*	*palmata*	−15.7		1
Ulvaceae	*Enteromorpha*	sp.	−9.6	−18.4	4, 5, 7
Ulvaceae	*Enteromorpha*	*marginata*	−16.6		6
Ulvaceae	*Ulva*	sp.	−4.9		5
Ulvaceae	*Ulva*	*taeniata*	−13.2	−17.8	1, 2
Ulvaceae	*Ulva*	*lactuca*	−10.2	−16.7	1
Vaucheriaceae	*Vaucheria*	sp.	−19.3		7
		Phytoplankton and benthic diatoms			
Diatom bloom	(mostly *Skeletonema costatum*)		−18	−24.7	3
Dinoflagellate	*Kreyptoperidinium* sp.		−20		3
Benthic algae	(mostly diatoms)		−16.2	−17.9	3

* References: 1) DeNiro and Epstein, 1978; 2) Fenton and Ritz, 1988; 3) Haines and Montague, 1979; 4) Jackson *et al.*, 1986; 5) Schwinghamer *et al.*, 1983; 6) Smith and Epstein, 1970; 7) Sullivan and Montcreiff, 1990

ceous estuarine marshes, which by definition are devoid of tree canopy.

Variations in plant metabolism can result in fractionation of $^{13}CO_2$. Plants with CAM can fix and store CO_2 causing additional fractionation in addition to that associated with the Hatch-Slack pathway. In many CAM plants, this function may be "switched on" when needed in times of drought or stress; thus, the $\delta^{13}C$ of plant carbon of CAM species may be highly variable, depending upon the environment (Kluge and Ting, 1978). There has been concern that the $\delta^{13}C$ of other species may vary with habitat, particularly in those which present additional stress. A recent study of three mangrove species (Lin and Sternberg, 1992) has shown differences in the $\delta^{13}C$ of mangroves which parallel morphological characteristics. Mangroves growing in scrub forests, with waterlogged and extremely saline soils, are generally smaller in this stressful habitat. They also have leaf carbon isotope ratios 1 to 4.0‰ higher than that of leaves from individuals of the same species, which are larger and growing in better conditions in the fringe forest. All the mangrove $\delta^{13}C$ values, however, were in the range reported for C-3 plants. No significant differences have been reported in the two forms (ecotypes) of *Spartina alterniflora* which are commonly found in a single salt marsh. Along the banks of creeks where drainage is good, *Spartina alterniflora* is found in the "tall form". A much shorter form is found higher in the marsh where drainage is hindered and anaerobic soil conditions predominate, causing metabolic stress in this species (MENDELSSOHN and MCKEE, 1988). The $\delta^{13}C$ of both short and tall *S. alterniflora* has been measured by BENNER *et al.* (1987) and HAINES (1976); little difference has been detected in the $\delta^{13}C$ of plant carbon in the two forms. There seems to be limited research on such variation within other herbaceous wetland species.

Stable carbon isotopic ratios from marine benthic macroalgae are extremely variable (Table 2). Under isotopic equilibrium, molecular CO_2 in seawater is virtually identical to atmospheric CO_2 whereas HCO_3^- is 9 to 7‰ heavier than molecular CO_2 in the temperature range of 0–30°C (DEUSER and DEGENS, 1967). Thus, differential use of bicarbonate and dissolved CO_2 by aquatic plants could cause variation in $\delta^{13}C$ values (BENEDICT *et al.*, 1980). Some researchers report an increase in the $\delta^{13}C$ of marine plankton with surface water temperatures (SACKETT *et al.*, 1965; FONTUGNE and DUPLESSY, 1981), but causes of all variations observed are still not clear. WIENCKE and FISCHER (1990) analyzed the carbon isotope composition of macroalgae in relation to light and temperature. They found that primary CO_2 availability in seawater, in association with carbon uptake and growth rates of algae, was the most important factor determining stable carbon isotope ratios.

CONCLUSIONS

Plant community structure can serve as a useful predictor of the $\delta^{13}C$ of organic carbon in autochthonous sediments. Carbon from CAM plants, however, may have variable $\delta^{13}C$ values which would be reflected by the $\delta^{13}C$ of the sedimentary organic matter. The $\delta^{13}C$ of sedimentary organic matter from communities in which CO_2 is subject to considerable recycling among the plants, such as forests with closed canopies, may reflect fractionation during recycling and vary from model predictions. More research on these systems would help to provide analogues for interpretation of paleo-environments.

Our evaluation of estuarine marshes of eastern North America and southern California, as well as studies by DELAUNE (1986) and CHMURA *et al.* (1987) on the northern coast of the Gulf of Mexico have indicated that $\delta^{13}C$ values of sedimentary organic matter would provide reliable evidence of the salinity regime of marsh deposits in these regions. In all three regions the pattern of $\delta^{13}C$ values in a transgressive sequence would reflect the pattern which corresponds to the estuarine sequence from saline to freshwater marsh depicted in Figures 1, 2, and 3. In a sequence capped by salt marsh deposits of $\delta^{13}C$, values would decrease with depth to a minimum which corresponds to carbon sources from terrestrial or a freshwater marsh environment. This pattern may not be reflected in a progressive decrease of $\delta^{13}C$ values in environments where C-4 plants can be locally dominant in freshwater marshes, such as that depicted for the southeastern coast of the United States (Figure 2). Consideration of $\delta^{13}C$ values at multiple depths in a stratigraphic context should help in detection of such anomalies.

A pattern of increasing $\delta^{13}C$ values with depth would be expected in a regressive sequence, but interpretations of these sequences would be more tenuous. If regression is concurrent with an increase to depth of the surface water table, an acceleration of decomposition may be expected. Continuous decomposition would likely cause a negative shift of $\delta^{13}C$ values in salt marsh deposits, masking their signature.

In addition to decomposition, excessive inputs of allochthonous carbon would cause a negative shift in the $\delta^{13}C$ of a salt marsh deposit and misrepresent the salinity, suggesting a concentration below that actually present at the time of deposition. Such problems can be alleviated by examining deposits for the presence of detrital organics or indications of erosional surfaces where exposure to aerobic conditions may have occurred.

Stable carbon isotope analyses is an accessible methodology since analysis of bulk sediments for $\delta^{13}C$ requires minimal preparation (CHMURA *et al.*, 1987) and can be conducted by commercial laboratories, if not already reported as a result of ^{14}C-dating by AMS methods. Thus stable carbon isotopes analysis could serve as a useful exploratory tool in regional studies where sea level rise histories are reconstructed from a large suite of cores.

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