

Carbon Dioxide Emission and Carbon Accumulation in Coastal Wetlands

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Direct measurements of CO₂ fluxes were made in salt, brackish and freshwater marshes and parallel adjacent open water areas in Barataria Basin, Louisiana. Vertical flux density was determined by monitoring the accumulation of CO₂ in aluminum chambers placed over the water or sediment surfaces. Annual CO₂ fluxes were 418, 180 and 618 g C m⁻² from the salt, brackish and freshwater marsh, respectively. Water bodies adjacent to the marsh evolved 103, 54 and 242 g CO₂ C m⁻² yr⁻¹ to the atmosphere from saline, brackish and freshwater lakes, respectively. The role these marshes play in serving as a major carbon sink was determined from the carbon content of the sediment, vertical accretion rates and the bulk density of the sediment. Accretion rates were calculated from the depth in the sediment of the 1963 horizon, the year of peak ¹³⁷Cs fallout. Net carbon accumulation was essentially the same in all three marshes; 183, 296 and 224 g C m⁻² yr⁻¹ from the salt, brackish and fresh marsh, respectively. Data presented suggest a limited net export of carbon from these coastal marshes. A large percentage of fixed carbon remained on the marsh, being immobilized in accretionary processes or lost to the atmosphere as CO₂.

Introduction

There is considerable interest in the role carbon plays in the detritus based food chain of estuarine ecosystems. Carbon dioxide production and subsequent release to the atmosphere are important processes in the overall carbon budget in coastal wetlands and need to be quantified. Carbon dioxide is a product of the biological oxidation of organic carbon by oxygen and/or other electron acceptors such as NO₃⁻, and SO₄²⁻. It includes three biological processes, namely, microbial respiration, root respiration and faunal respiration and a non-biological chemical oxidation, which may be pronounced at high temperatures (Bunt & Rovira, 1954). In waterlogged marsh soils the diffusion of oxygen into the soil is restricted resulting in the formation of a largely anaerobic environment with small aerobic zones at the surface and around roots (Teal & Kanwisher, 1966). Much of the metabolism occurs anaerobically and involves the oxidation of organic carbon to carbon dioxide using the oxygen contained in the SO₄²⁻ ion as the electron acceptor (Jorgensen, 1978).

Respiration or decomposition has been estimated by indirect techniques in marsh soils. The approaches used include the measurement of the disappearance of particulate matter, the consumption of the electron acceptors oxygen or sulfate and the turnover of specific dissolved organic compounds (Christian and Wiebe, 1978; Hackney & de la Cruz, 1980;

Jorgenson, 1978). Most reports on carbon dioxide evolution are from upland agricultural soils and forest ecosystems (Gupta & Singh, 1981; Reinke *et al.*, 1981). To date there have been few *in situ* carbon dioxide flux measurements from coastal marshes.

Barataria Basin, in which this study was conducted, is an interdistributary basin bounded on the east by the Mississippi River and on the west by Bayou Lafourche. In recent years the basin had been deprived of riverine deposits through natural stream diversion and flood control measures. Barataria Basin is thus a well defined hydrologic unit containing more than 371 914 hectares of marsh and open water (Day *et al.*, 1973). Salinity decreases with increasing distance from the coast. Freshwater marshes cover 19% of the basin and brackish marshes cover 20% of the basin. Salt marshes near the coast cover approximately 14% of the basin and are widely interspersed with open water bodies.

In this paper we present data quantifying seasonal fluxes of carbon dioxide from Barataria Basin fresh, brackish, and salt marshes and adjoining water bodies located along a salinity gradient perpendicular to the Gulf Coast. In addition we identify the role of the aggradation process of vertical accretion in serving as a large carbon sink in Louisiana Gulf Coast marshes.

Materials and methods

The emission of carbon dioxide was measured from the three predominant marsh types found within Barataria Basin (Figure 1). *Spartina alterniflora*, *Spartina patens*, and

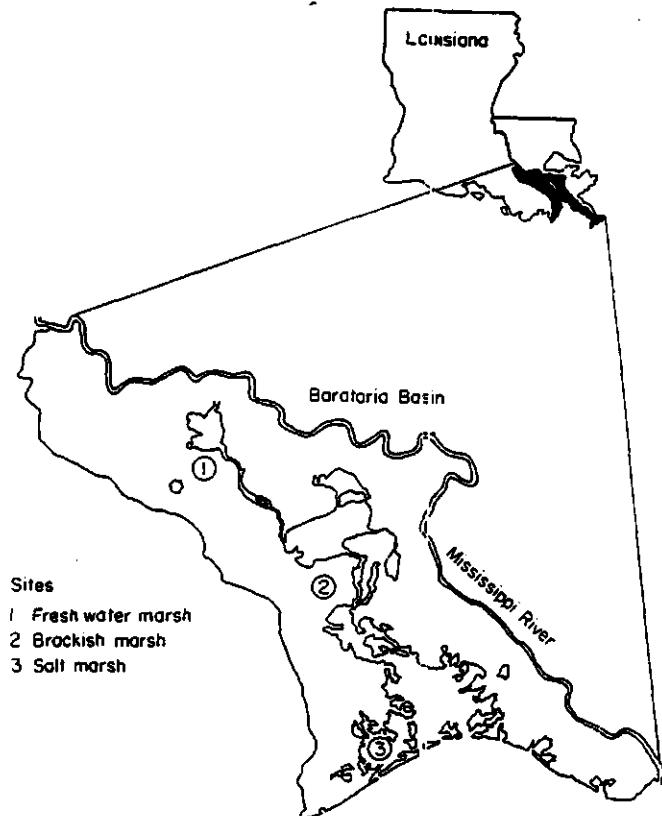


Figure 1. Location of study area.

Panicum hemitomon are the most abundant plant species found in the salt, brackish and freshwater marshes, respectively. These marshes have been described extensively elsewhere (Kolb and Van Lopik, 1966; Day *et al.*, 1973; DeLaune *et al.*, 1982). Carbon dioxide emissions from each marsh environment and their adjacent open water areas were determined at approximately six week intervals during 1980 and 1981.

The vertical carbon dioxide flux density was estimated by monitoring accumulation of the gas beneath chambers placed over the water or sediment surface, for a maximum of one hour (DeLaune *et al.*, 1982). The chambers were light proof which prevented any photosynthesis. A similar diffusion chamber technique has been used by King & Wiebe (1978) and Oremland (1975) to estimate methane emission. Triplicate determinations were made in the freshwater and salt marshes and duplicate determinations in the brackish marsh on each sampling date. The marsh vegetation was clipped and removed prior to making the measurements. The chambers were fabricated from aluminum cylinders, 41 cm internal diameter and had an effective internal height of 10 cm above the water or sediment surface. Chambers 15 cm tall were used for flux determination on the open water bodies and when water was covering the marsh. These chambers were supported by styrofoam collars positioned such that 5 cm extended below the air-water interface. When the marsh was drained the chambers were placed on permanent bases previously installed in the marsh to minimize physical disturbance of the sediment. The permanent bases were constructed from P.V.C. pipe (5 cm length, 36 cm diameter) pushed into the sediment and a top plate (washer shaped) which had a 2 cm × 1 cm deep U-shaped groove. Water was placed in this groove to provide a seal between the chamber and the base.

The chambers were shaded at all times, thereby minimizing the air temperature increase within the chamber during flux measurements. The chambers used on the open water bodies were insulated with liquid foam and covered with a reflective space blanket. The top of the chambers were fitted with an air sampling port constructed from a 0·6 cm Swagelock bulk-head union modified for gas-chromatographic septum penetration and a vent port constructed from a 1·2 cm Swagelock bulk-head union. An open ended tube (0·6 cm outside diameter × 100 cm long) was attached to the vent port, thereby allowing pressure equilibration without entry of outside air during sampling. The vent port was capped on the chambers used on the open water bodies. Aliquots (10 cm³) of the atmosphere within the chamber were withdrawn at 10 min intervals (0–60 min) into glass syringes which were greased with Apeizon N and sealed with Pharmaseal Teflon 3-way plastic valves (Dowdell *et al.*, 1972). The samples were collected by passing an 8 cm hypodermic needle through the air sampling port.

Carbon dioxide content of the gas samples was determined on a Varian 3700 gas chromatograph equipped with a flame ionization detector (FID) operated at 340°C and a catalytic conversion unit operated at 400°C (Williams *et al.*, 1972). The catalyst oven was added between the column exit and the FID inlet (Smith *et al.*, 1981). The air samples were injected using a heated gas sampling valve (40°C) with a 0·25 cm³ sampling loop onto a Porapak N column (80/100 mesh; 5 m long × 0·2 cm internal diameter) maintained at 50°C. The carrier gas was dinitrogen and the flow rate was controlled at 30 cm³ min⁻¹. Peaks were integrated on a Varian CDSIII integrator and compared to standards. Carbon dioxide fluxes were computed from the concentration increase within the headspace of the chamber (Smith *et al.*, 1981).

Vertical marsh accretion and sedimentation rates in the bottom of adjoining shallow water lakes was determined using ¹³⁷Cs dating technique (DeLaune *et al.*, 1978). Sedimentation or accretion rates were calculated from the depth in the soil or sediment of the 1963

horizon, the year of peak ^{137}Cs fallout, a result of atomic weapon testing. Cores were taken at each site, sectioned into 3 cm increments, dried and ground, and each sample well mixed. The ^{137}Cs activity in each section was determined by γ counting of the oven-dried sample using a lithium-drift germanium detector and multichannel analyser. Total carbon content of the sediment was determined by dry combustion. Density was determined from oven-dry sediment in the known volume of each section. The net carbon accumulation was calculated from the carbon content of the sediment, the accretion rate, and the bulk density of the sediment.

Results

Accretion on sedimentation rates in marshes and lake bottoms are shown in Table 1. Net accretion was essentially the same for all marsh types studied, ranging between 0.76 and 1.1 cm yr^{-1} . Calculations using soil bulk density data, accretion rates and organic carbon content show that annual carbon accumulation was essentially the same in all three marshes studied, ranging between 183 and 296 g $\text{C m}^{-2} \text{ yr}^{-1}$. The annual rates of carbon accumulation was less in the freshwater bottom sediment than in the saline bottom sediment (Table 1). In these computations allowance was made for the variation in the mineral sediment content of the marshes.

TABLE 1. Accumulation rates of carbon and net accretion rates

Marsh type	Site ^a	Accretion rate (cm yr^{-1})	Bulk density (g cm^{-3})	Organic carbon (mg g^{-1})	Carbon accumulation (g $\text{C m}^{-2} \text{ yr}^{-1}$)
<i>Spartina alterniflora</i> (salt)	M	0.76 ± 0.12	0.28 ± 0.06	86 ± 16	183
	B	1.1 ± 0.1	0.57 ± 0.01	38 ± 12	238
<i>Spartina patens</i> (brackish)	M	0.95 ± 0.05	0.13 ± 0.02	240 ± 32	296
	B				
<i>Panicum hemitomon</i> (fresh)	M	0.85 ± 0.02	0.10 ± 0.04	263 ± 14	224
	B	0.52 ± 0.2	0.26 ± 0.05	45 ± 16	60

^aM—Marsh surface; B—bottom sediment from open water areas.

The seasonal emissions of carbon dioxide for the three marshes are shown in Figures 2, 3 and 4. The average daily carbon dioxide emissions from the salt, brackish and freshwater marshes were 1150, 490 and 1690 mg C m^{-2} , respectively. Not shown in Figures 2, 3, and 4 is the spatial variability of the CO_2 flux measurements. Points plotted in the figures represent the mean of three individual determinations having coefficients of spatial variability averaging 60, 55 and 72 over the 12 sampling dates for the salt, brackish, and freshwater marsh, respectively. Similar diversity in field flux measurements has been reported for CH_4 (King & Wiebe, 1978; DeLaune *et al.*, 1982) and N_2O (Mosier & Hutchinson, 1981; Bremner *et al.*, 1981). The carbon dioxide emission was equivalent to an average annual loss of 418, 180 and 620 g C m^{-2} , respectively, for the salt, brackish, and freshwater marshes (Table 2).

There was an apparent seasonal trend in the carbon dioxide evolution for all three marshes which was found to be statistically significant. Carbon dioxide evolution was directly related to the sediment and air temperature ($P < 0.05$). Generally the carbon

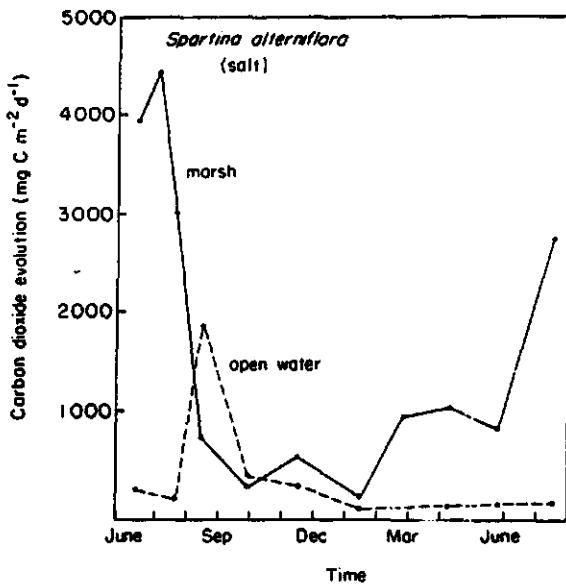


Figure 2. Seasonal carbon dioxide release from salt marsh.

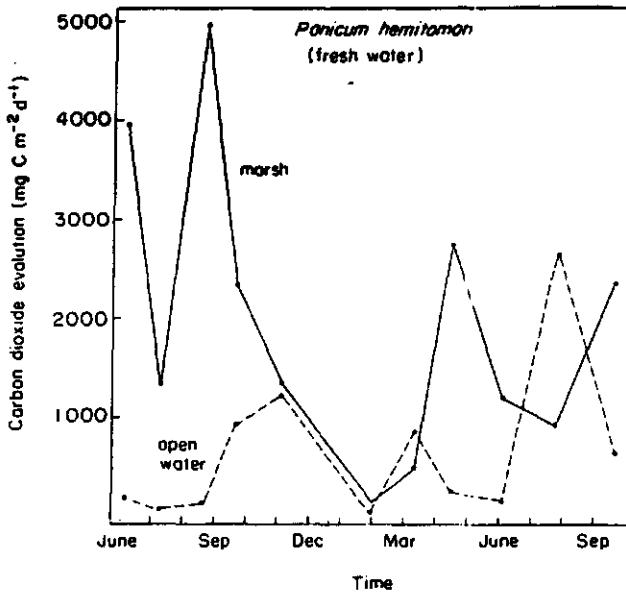


Figure 3. Seasonal carbon dioxide release from brackish marsh.

dioxide evolution was greater during the summer period when temperatures were high as compared to the winter months. However, the vertical flux of carbon dioxide to the atmosphere was found to have an inverse relationship with depth of water inundating the marsh ($P < 0.05$). Multiple correlation of carbon dioxide flux vs temperature and water depth improved the correlation coefficient, which became highly significant ($P \leq 0.001$).

There was considerably less carbon dioxide evolution from the open water bodies adjacent to the three marsh sites (Table 3). The open water bodies adjacent to each marsh had

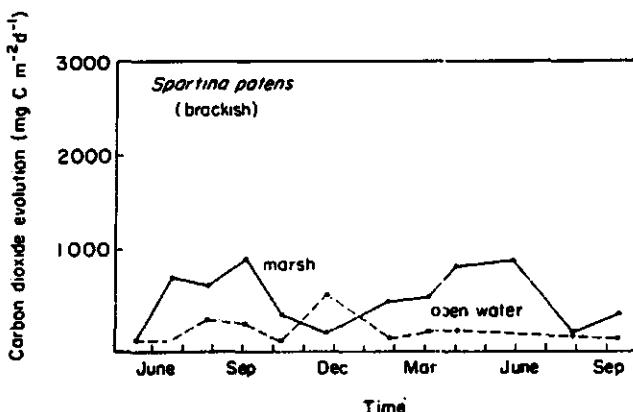


Figure 4. Seasonal carbon dioxide release from freshwater marsh.

TABLE 2. Carbon dioxide emission from the three predominant marsh soils found within Barataria Basin

Marsh type	Measurement period (days)	Carbon dioxide emission		
		total g C m⁻²	average g C m⁻² d⁻¹	annual g C m⁻²
<i>Spartina alterniflora</i> (salt)	396	453	1.15	418
<i>Spartina patens</i> (brackish)	486	239	0.49	180
<i>Panicum hemitomon</i> (fresh)	452	762	1.69	616

^aMean of three determinations from each marsh, and the flux determined 12 times during 1980-1981.

TABLE 3. Diffusive emission of carbon dioxide from the open water bodies found within Barataria Basin

Location	Measurement period (days)	Carbon dioxide evolution		
		total g C m⁻²	average g C m⁻² d⁻¹	annual g C m⁻²
<i>Spartina alterniflora</i> (salt)	396	112	0.28	103
<i>Spartina patens</i> (brackish)	486	72	0.15	54
<i>Panicum hemitomon</i> (fresh)	452	300	0.67	242

^aCarbon dioxide flux determined 12 times during 1980-1981.

an average depth of approximately 100 cm as compared to an average depth of less than 10 cm of water overlying the marsh. Thus potentially a greater amount of carbon dioxide escaping from the bottom sediment would have been dissolved in the relatively deeper water. The average pH of the water ranged from 7.0 in the freshwater lake to 7.5 in the

salt water lake. The carbon dioxide fluxes from the open water sites ranged from 103 mg C m⁻² d⁻¹ at the salt water site near the coast to 242 mg C m⁻² d⁻¹ from the freshwater site. The dissolved carbon dioxide content of the open water was not significantly different among the three sites and ranged from 2 to 14 mg CO₂ l⁻¹ throughout the year. The total carbon dioxide content of the water ranged from 0.5 to 3.8 g CO₂-C m⁻².

Discussion

Carbon dioxide is not necessarily the only respiratory product in anaerobic marsh soils and sediments. Under intensely anaerobic conditions carbon dioxide can be further reduced to methane by methanogens. Thus some of the carbon dioxide produced in the anaerobic sediment can be reduced as it diffuses through the sediment. Methane, the terminal product of metabolism is a non-toxic mobile substance and an important component of the carbon cycle in anoxic environments. The carbon dioxide which is not utilized as an electron acceptor is returned to the atmosphere by diffusion or ebullition or could be conducted through the continuous gas spaces from shoots to rhizomes and roots. Oxygen diffuses through these spaces into the sediment (Teal & Kanwisher, 1966), and carbon dioxide could also diffuse to the atmosphere. Although the marsh vegetation was clipped prior to placing the diffusion chamber over the marsh we do not believe the carbon dioxide fluxes were significantly affected since carbon dioxide would still have direct passage from the marsh soil through the cut stems. Cicerone & Shetter (1981) reported no differences in methane flux measured from cut and intact rice plants.

Earlier carbon budgets developed for coastal marshes have not included gaseous carbon fluxes. Gaseous evolution of carbon dioxide and methane was not included in a carbon budget developed for Barataria Basin by Day *et al.* (1973). Similarly, Woodwell *et al.* (1977) did not include gaseous carbon emission in a carbon study of a Northeastern US Flax Pond ecosystem. Data presented in this study show that a significant amount of fixed carbon in the various marshes found in Louisiana Barataria Basin is returned to the atmosphere (Table 2). However not all the carbon dioxide evolved from marsh soil is lost from the soil/plant system, a portion of carbon dioxide evolved is taken up by marsh plants via photosynthetic processes. The contribution of soil carbon dioxide flux to plant photosynthesis has been estimated for various submerged and nonsubmerged plants (Yoshida *et al.*, 1974; Monteith *et al.*, 1964; Nixon, 1980). Soil CO₂ contribution to the gross photosynthesis in various upland crops (Monteith *et al.*, 1964) ranged between 10 to 40% and contributed 6% of the CO₂ fixed by rice grown under flooded conditions (Yoshida *et al.*, 1974). Nixon (1980) cites 40% of the plant biomass as being produced from carbon dioxide evolved from the surface of a Flax Pond marsh. He reported annual plant production was 500 g C m⁻²; 200 g C m⁻² coming from the carbon dioxide evolved from the surface, and 300 g C m⁻² from new atmospheric carbon dioxide. No value was reported for the total carbon dioxide evolution from the marsh surface and it is not known what fraction of the soil flux this represents. For the marshes under study the total gaseous carbon emission as carbon dioxide and methane can be calculated by summation of the annual fluxes for the two gases. Previously reported annual methane flux for these Barataria Basin salt, brackish, and fresh marshes was 4.3, 73 and 160 g CH₄-C m⁻², respectively (DeLaune *et al.*, 1982). Thus the total annual gaseous carbon evolution as CO₂ and CH₄ is equivalent to 422, 253 and 776 g C m⁻² for the salt, brackish and freshwater marshes, respectively.

Evolution from the open water bodies to the air was lower than that observed for the marsh itself. The total evolution from the bottom sediment was very likely greater than

the measured atmospheric evolution due to the formation of inorganic carbon compounds in the water. Carbon dioxide flux was also less from the marsh when it was inundated with water. The bottom sediment in open water adjoining the marshes are also a sink for organic carbon, the magnitude of which is shown in Table 1. However, significantly more carbon accumulates in the marsh than in the bottom sediment of open water bodies.

Carbon dioxide evolution during the summer months in this study was similar to that reported for flooded rice soils (Yoshida *et al.*, 1974). They found the flux to range from 1·6 to 2·4 g C m⁻² d⁻¹, whereas emission from the marshes in this study ranged from 1 to 5 g C m⁻² d⁻¹. The carbon content of the marsh soil in this study was significantly greater than the paddy soil which would result in the increase in the carbon dioxide release. Emissions from forest soils varied from 400 to 510 g C m⁻² (Reinke *et al.*, 1981) which was greater than the annual evolution from the marsh sediment. Respiration from grasslands has been reported to be 360, 420, and 470 g C m⁻² y⁻¹ (Coleman, 1973; Gupta & Singh, 1981).

Carbon evolution in the salt marsh has been previously estimated by measurement of oxygen consumption (Hopkinson, 1973). The streamside consumption was equivalent to 395 g C m⁻² y⁻¹ and inland consumption equivalent to 260 g C m⁻² y⁻¹ based on measurements in the vicinity of our study site (Hopkinson, 1973). These calculated estimates are similar to the CO₂ fluxes reported (418 g C m⁻² y⁻¹). The net annual marsh production in the vicinity of our site has been calculated to be 1175 g dry wt m⁻² or 590 g C m⁻² (Kirby & Gosselink, 1976). Happ *et al.* (1977) used this productivity figure and the carbon emission based on oxygen consumption measurements to estimate organic carbon available for export. They estimated 290 g C m⁻² y⁻¹ to be flushed from the marsh. However, the amount of carbon accumulating during the process of vertical accretion was not included in the calculation. Due to rapid subsidence large amounts of organic material formed from primary production remain on the marsh mainly as peats as part of aggradation processes involved in keeping the marsh intertidal.

The annual carbon accumulation obtained by ¹³⁷Cs dating and the gaseous evolution data reported in this paper strongly suggests a limited net loss of fixed organic carbon from the Louisiana salt marsh. Marsh accretion processes serve as a sink for 183 g C m⁻² y⁻¹ and an additional 418 g C m⁻² y⁻¹ is evolved from the marsh surface as CO₂ and CH₄ and a major portion of the CO₂ is returned to the atmosphere. These two carbon fluxes closely approximate the net production reported by Kirby & Gosselink (1976) for this particular salt marsh. There is limited productivity data for the fresh and brackish marshes thus it is not possible to make similar estimates of net carbon export from the marsh. The carbon fluxes presented question the traditional view of marshes as large net exporters of fixed carbon. A large portion of carbon fixed in Louisiana Barataria Basin either remain on the marsh mainly as peat deposits or is degraded and released to the atmosphere as carbon dioxide and/or methane. Woodwell *et al.* (1977) showed a tidal marsh on the north shore of Long Island to be a net consumer of chlorophyll throughout the year and a strong heterotrophic system in summer which does not support the conventional view of marshes as a net source of fixed carbon to coastal waters. Haines (1977) studies of δ¹³C ratio of organic matter in Georgia estuaries also supports the data presented that fixed carbon is not exported with each tidal inundation.

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