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Effects of Impoundment on Vertical Accretion of Coastal Marsh

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ABSTRACT: Vertical accretion of impounded marsh and adjacent natural marsh at four sites in southwestern Louisiana was estimated in 1994 by determining the depth of a stratum containing ^{137}Cs deposited in 1963. With relative marsh elevation, soil bulk density, organic matter content, and organic and mineral matter accumulation rates were used to describe soil formation. Three sites were impounded in 1956 and one site in 1951. Impounded marshes had lower marsh surface elevation than natural marshes because of hydrologic isolation from tidal sediment subsidies and substrate oxidation during forced drying. The elevation of natural marshes ranged from 12 cm to 42 cm higher than the elevation of the impounded marshes in 1963 and from 20 cm to 32 cm higher in 1994. Vertical accretion between 1963 and 1994 ranged from 9 cm to 28 cm in impounded marsh and from 15 cm to 21.5 cm in natural marsh. Only in impounded marsh that remained permanently flooded was accretion greater than in natural marsh.

Introduction

Impoundments have been used for more than 40 yrs in Louisiana to manage hydrological regimes and improve habitat for waterfowl and furbearers in coastal marshes (Chabreck 1988). Impoundments are surrounded with levees and have gated culverts or pumps for controlling water levels and salinities to produce a desired density and species composition of plants (Chabreck 1960). Impoundments on state and federal lands encompass 37,000 ha in Louisiana (Day et al. 1990) and compose 17% of the inland area of the Chenier Plain (Gosselink et al. 1979).

Sedimentation and accretion are important processes for maintaining the elevation of coastal marshes in relation to sea level (Hatton et al. 1983). And, in coastal Louisiana, input of sediment to marshes is important in offsetting sea-level rise (Cahoon 1994). The levee system used to form a marsh impoundment provides a barrier to water movement and restricts mineral sediment input. Sedimentation is the deposition of mineral and organic matter on marsh substrate (Nyman et al. 1993b). Accretion is the net building of marsh soils (Turner and Cahoon 1987; Van Gent 1988; DeLaune et al. 1989) and is achieved through the combination of mineral and organic matter accumulation (DeLaune et al. 1989). Accumulation of organic matter is influenced by plant production and decomposition (Nyman et al. 1993a) and regulates soil formation in Louisiana coastal marshes (Nyman et al. 1993b). Impaired plant production adversely affects not only aboveground production but also belowground production of organics (Hatton et al. 1983).

Subsidence and eustatic sea-level rise contribute to the loss of coastal marsh in Louisiana (Baumann 1980; Boesch et al. 1983; Titus 1986). Sea-level rise for the Chenier Plain measured at Cameron, Louisiana, from 1954 to 1980 was 1.2 cm yr^{-1} (DeLaune et al. 1983). To offset the actions of subsidence and sea-level rise, coastal marshes must perpetually accrete mineral sediment and organic matter (Boesch et al. 1983). Studies of vertical accretion rates in Louisiana indicate that coastal marshes are not accreting fast enough to maintain their existence in the intertidal zone (DeLaune et al. 1983). Boumans and Day (1994) reported that impoundment of marsh may further lead to a sediment deficit.

The purpose of this study was to determine the long-term accretion rate and marsh elevation at several sites in southwestern Louisiana in impounded marshes and adjacent natural marshes and to compare several factors that affect soil formation under different impoundment systems.

Study Methods

Management units examined were in tidally influenced marsh in the Chenier Plain and inland 1.5–11.0 km from the Gulf of Mexico in southwestern Louisiana (Fig. 1). The management units (impounded marsh) were on Marsh Island Wildlife Refuge (unit 1), Rockefeller Wildlife Refuge (units 14 and 15), and Sabine National Wildlife Refuge (unit 3) and were constructed between 1951 and 1956 (Table 1). Annual temperature averages 20°C

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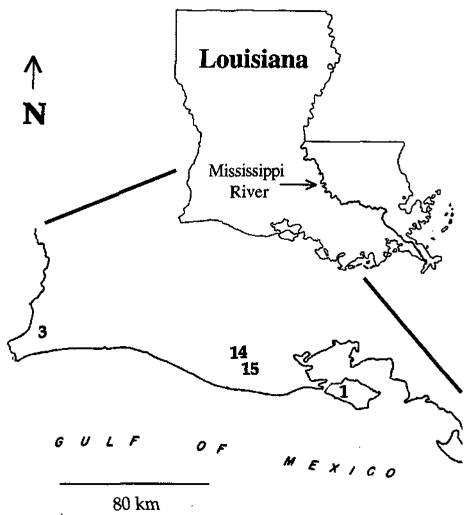

Fig. 1. Location of study areas along the Louisiana coast. Numbers on the map identify study sites with 1 = Marsh Island Wildlife Refuge Unit 1 (29°31'45"N, 91°54'02"W), 15 = Rockefeller Wildlife Refuge Unit 15 (29°37'50"N, 91°32'08"W), 14 = Rockefeller Wildlife Refuge Unit 14 (29°38'42"N, 92°34'22"W), and 3 = Sabine National Wildlife Refuge Unit 3, (29°52'30"N, 93°32'30"W).

TABLE 1. Construction date, distance from Gulf of Mexico, size, and management type for impounded marshes at selected sites in southwestern Louisiana, 1994.

Site	Date constructed	Distance from Gulf (km)	Size (ha)	Management type
Marsh Island[a] Unit 1	1956	1.5	3,200	periodic drying
Sabine NWR[b] Unit 3	1951	11.0	10,688	permanent flooding
Rockefeller[c] Unit 14	1951	7.0	972	periodic drying
Rockefeller[c] Unit 15	1951	7.0	364	periodic drying

[a] Mouton (1996).
[b] Personal communication, John Walther.
[c] Wicker et al. (1983).

and precipitation averages 145 cm (Chabreck 1972); an extended growing season and abundant rainfall are conducive to vigorous plant growth. Winter storms influence these areas by pre-frontal wind and wave action that elevates water levels in bays nearly 61 cm and increases sediment flux (Roberts et al. 1989). Storm events play an increasingly important role in sediment transport to coastal marshes in southwestern Louisiana as the Atchafalaya Delta continues its progradation (Roberts et al. 1989).

Selection of sampling sites at each study area was based on the presence of impounded and adjacent natural marshes that were separated by the impoundment levee. The sites were sampled in June and July 1994. Soil cores were collected 20 m and 30 m into each marsh from the levee. Elevation readings were taken on the surface of the marsh. Marsh elevation at a sampling site was determined with an automatic level placed on top of the levee and referenced to a temporary bench mark established on the levee. Elevation of the impounded marsh and natural marsh was determined with the level in one position. We assumed that the marsh elevation at sampling stations at each site in impounded marsh and natural marsh was the same when the marsh was impounded.

A soil core was removed using a thin-walled aluminum cylinder (50 cm long and 15 cm diameter) that was pressed into the soil. The core was extracted, extruded from the cylinder into a wooden trough, immediately cut into 2-cm sections, and bagged to minimize the effects of dewatering, agitation, or compaction associated with transport. Sections were dried at 80°C to remove nonstructural water and ground in a soil mill. The ^{137}Cs level of each ground section was determined by counting in a Marinelli beaker fitted over an intrinsic Ge detector crystal coupled to a multichannel analyzer (DeLaune et al. 1978; Hatton et al. 1983). The ^{137}Cs maxima was assumed to correspond to 1963 marsh surfaces exposed to deposition from nuclear weapons testing and provided a reference for estimating vertical accretion (DeLaune et al. 1978; Milan et al. 1995).

Bulk density and organic matter content of each core were calculated from the ground sections. Combustion at 400°C for 16 h was used to determine the organic matter content of each section (Davies 1974; Nyman et al. 1993b). Organic and mineral matter accumulation were calculated by multiplying accretion rate by bulk density and percentage organic-mineral content (Cahoon 1994).

Vertical accretion estimates, soil bulk density, soil organic matter content, organic matter accumulation, mineral matter accumulation, and relative elevation were statistically analyzed for each site in relation to treatment (impounded and natural). For this analysis of variance, t-statistics were derived at the 0.05 alpha level (Proc GLM; SAS Institute Inc., Cary, North Carolina). Multiple comparisons of the impoundments and controls were performed using a Bonferroni t-test for each of the variables to illuminate characteristics shared between the sites. Relationships between the variables were determined by correlation analysis (Proc CORR; SAS Institute Inc., Cary, North Carolina).

Results

Comparisons Within Sites

The 1963 mean elevation of the natural marsh at unit 1 was 17 cm higher than the impounded

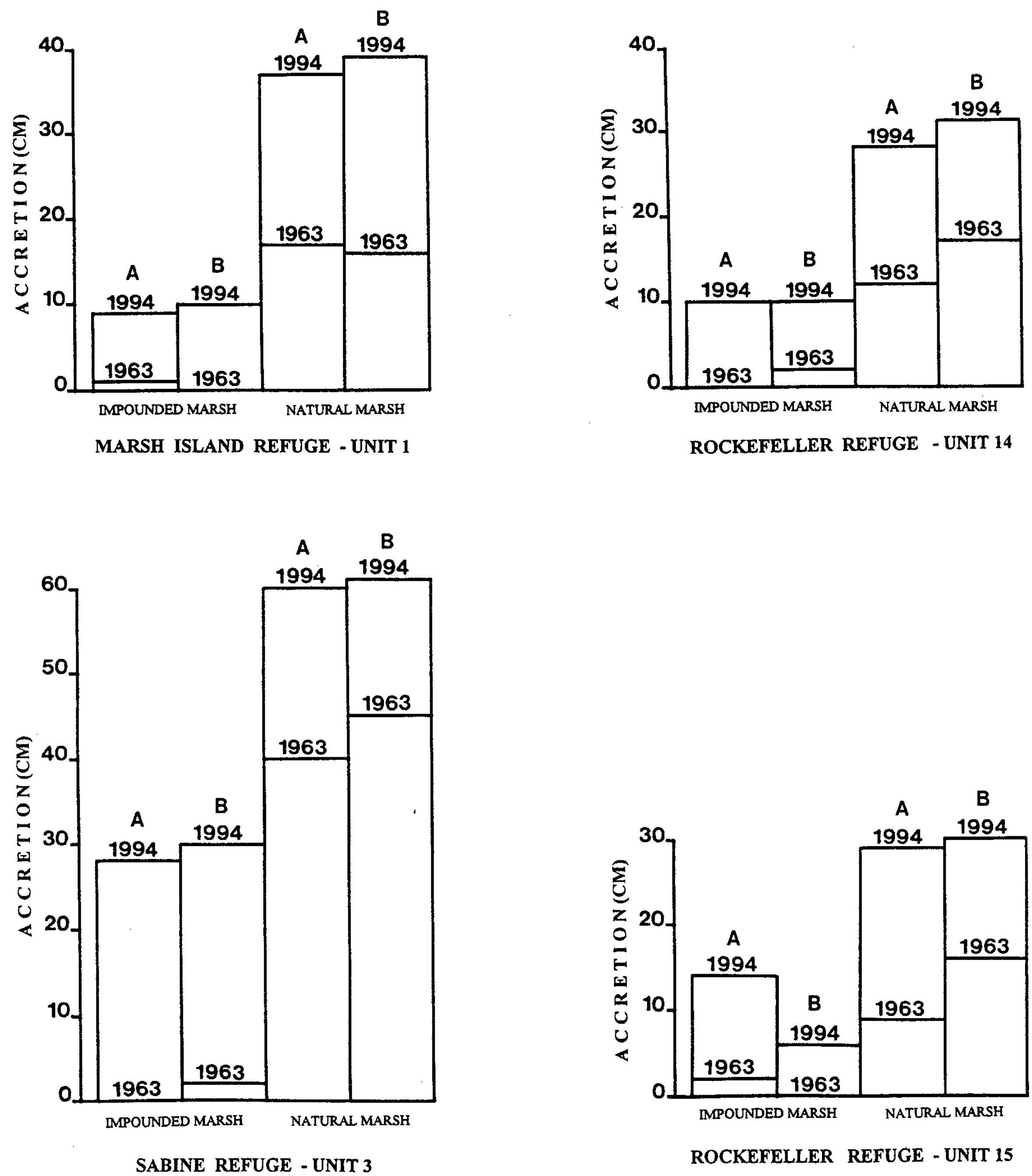

Fig. 2. Relative position of the marsh surface at sample stations A and B in impounded marsh and adjacent natural marsh in 1994 at four sites in coastal marsh in southwestern Louisiana. The marsh at all sites was impounded in 1956 or earlier and the relative position of the marsh surface in 1963 was determined by the depth to the soil layer with maximum ^{137}Cs concentration below the 1994 surface.

marsh ($p = 0.0001$), and in 1994 it was 29 cm higher than the impounded marsh ($p = 0.0001$; Fig. 2). The natural marsh had 139% greater mean accretion since 1963 than the impounded marsh ($p = 0.0014$; Table 2). Mean organic matter accumulation in the natural marsh was 116% greater than in the impounded marsh ($p = 0.0099$). Soil bulk density in the impoundment was 47% greater than in the natural marsh ($p = 0.0156$). No difference was found between the impounded and natural marshes in soil organic matter content ($p = 0.3123$) and mineral matter accumulation ($p = 0.2004$).

The mean elevation of the natural marsh at unit

TABLE 2. Mean[a] (n = 2) value of variables in impounded coastal marsh and adjacent natural marsh at selected sites in southwestern Louisiana, 1994.

	Management Units			
Variables	Unit 1	Unit 3	Unit 14	Unit 15
Impounded Marsh				
Accretion (cm; 1963–1994)	*9.0A	*28.0B	9.0A	*9.0A
Accretion Rate (cm yr^{-1})	*0.29A	*0.90B	0.29A	*0.29A
Relative Elevation (cm)	*46.3	*45.0	*51.2	*51.1
Bulk Density (g cm^{-3})	*1.1A	0.7A	0.8A	0.8A
Organic Matter Content (%)	24.9A	67.7B	36.2A	37.5A
O.M.[b] Accumulation (g m^{-2} yr^{-1})	*794.0A	*4265.0B	736.0A	*816.0A
M.M.[c] Accumulation (g m^{-2} yr^{-1})	2396.0A	2035A	1645.0A	*1309.0A
Natural Marsh				
Accretion (cm; 1963–1994)	21.5	18.0	15.0	17.0
Accretion Rate (cm yr^{-1})	0.70AB	0.59B	0.48B	0.55A
Relative Elevation (cm)	75.6	77.1	70.8	71.0
Bulk Density (g cm^{-3})	0.8AB	0.5B	0.6B	1.0A
Organic Matter Content (%)	34.0A	60.3B	38.8A	29.8A
O.M.[b] Accumulation (g m^{-2} yr^{-1})	1716.0A	1594.0A	1030.0A	1643.0A
M.M.[c] Accumulation (g m^{-2} yr^{-1})	3429.0A	1071.0A	1655.0A	3856.0A

[a] The mean of a variable in impounded marsh preceded by an asterisk was significantly different ($p < 0.05$) from the variable mean in natural marsh within the same unit. Mean values of a particular variable that are followed in rows by different letters are significantly different ($p < 0.05$).
[b] Organic Matter Accumulation.
[c] Mineral Matter Accumulation.

15 in 1963 was 12 cm higher than the impounded marsh (p = 0.0013), and in 1994 the mean elevation of the natural marsh was 20 cm higher than the impounded marsh (p = 0.0001; Fig. 2). The natural marsh had 89% greater mean accretion since 1963 than the impounded marsh (p = 0.0155; Table 2). Mean organic matter accumulation was 101% greater (p = 0.0173) and mean mineral matter accumulation was 195% greater (p = 0.0085) in the natural marsh than in the impounded marsh. No difference was found between the impounded and natural marshes in soil bulk density (p = 0.1446) and organic matter content (p = 0.3944).

The mean elevation of the natural marsh at unit 14 in 1963 was 14 cm higher than the impounded marsh (p = 0.0006), and in 1994 it was 20 cm higher than the impounded marsh (p = 0.0001; Fig. 2). Mean accretion since 1963 did not differ between impounded and natural marsh (p = 0.0506; Table 2), although the difference closely approached significance. No difference occurred between the impounded and natural marshes in soil bulk density (p = 0.1446), soil organic matter content (p = 0.3944), organic matter accumulation (p = 0.3175), and mineral matter accumulation (p = 0.9890).

The mean elevation of the impounded marsh in unit 3 in 1963 was 42 cm lower than the natural marsh (p = 0.0001), and in 1994 it was 32 cm lower than the natural marsh (p = 0.0001; Fig. 2). Mean accretion since 1963 was 56% greater in the impounded marsh than in the natural marsh (p = 0.0050; Table 2). Mean organic matter accumulation was 168% greater in the impounded marsh than in the natural marsh (p = 0.0001). No difference was found between the impounded and natural marshes in soil bulk density (p = 0.0692), soil organic matter content (p = 0.4099), and mineral matter accumulation (p = 0.2267).

Comparisons Among Sites

Mean accretion since 1963 in the natural marsh did not differ (p = 0.2833) among the four units. However, mean accretion since 1963 was greater in the impounded marsh at unit 3 than in units 1, 14, and 15 (p = 0.0028) but did not differ among units 1, 14, and 15.

Mean soil bulk density in the impounded marshes did not differ among sites (p = 0.1226). Unit 15 natural marsh had greater mean soil bulk density than the natural marshes at units 14 and 3 (p = 0.0108). We were unable to detect a difference between mean soil bulk density in the natural marsh of unit 1 and that of other sites.

Mean soil organic matter content in the impounded marshes did not differ among sites (p = 0.0707). Mean soil organic matter content was greater in the natural marsh at unit 3 than in the natural marshes at other sites (p = 0.0067). Mean organic matter accumulation was greater in the unit 3 impounded marsh than in the impounded marshes at other sites (p = 0.0003). Mean organic matter accumulation in the natural marshes did not differ among sites (p = 0.2522). Mean mineral matter accumulation in the impounded (p = 0.5119) and natural (p = 0.0553) marshes did not differ among sites.

Relationship Between Variables at Sites

In impounded marsh, a positive correlation occurred between vertical accretion and soil organic matter content, accretion and organic matter accumulation, and organic matter content and organic matter accumulation. Other correlations between variables in the impoundments were not significant. In the natural marshes, there was a positive correlation between accretion and organic matter accumulation, relative elevation and soil organic matter content, and soil bulk density and mineral matter accumulation.

Discussion

Impoundment levees apparently prevented flood delivery of mineral sediment into the impounded marshes during storm passage associated with a cold front (Reed 1989) and most hurricanes (Chabreck 1994) and reduced the accretion rate of impounded marshes. Boumans and Day (1994) noted a progressive sediment deficit in managed marsh on Rockefeller Refuge as compared to natural marsh. Mean accretion rates in the impounded marshes at units 1, 15, and 14 during our study (0.29 cm yr^{-1}) were about half those in adjacent natural marshes. Mean accretion rates in natural marsh at all sites were lower than the 0.78 cm yr^{-1} measured by DeLaune et al. (1983) in a marsh on the south shore of Calcasieu Lake, located 40 km west of Rockefeller Refuge. In a natural marsh at East Little Constance Bayou in Rockefeller Refuge, Cahoon (1994) ascertained a short-term accretion rate of 0.98 cm yr^{-1}, much higher than long-term accretion rates in natural marsh reported by DeLaune et al. (1983) and in this study ($\bar{x}$ = 0.58 cm yr^{-1}). However, Cahoon (1994) found a short-term accretion rate of only 0.12 cm yr^{-1} in impounded marsh at Rockefeller Refuge unit 4.

Baumann (1980) and Reed (1989) reported that most sedimentation in Louisiana coastal marshes occurred during winter storm passages, but Nyman et al. (1995) noted that hurricanes substantially increase sedimentation. Hurricanes offer the potential of mineral sediment delivery over impoundment levees; however, hurricanes that overtop the levees seldom occur and also may damage levees and inhibit soil formation by the removal of organic material (Ensminger and Nichols 1957). High energy storms have been linked to depositional and erosional impacts on coastal marshes. Rejmanek et al. (1988) documented the deposition of 2 cm of mineral sediment in a *Phragmites australis*-dominated marsh in Louisiana following the passage of a hurricane. Meeder (1987) documented the sediment delivery potential of a hurricane when he captured over 6 cm of mineral sediment in a trap during the passage of Hurricane Juan; however, he also noted that heavy rains washed the unconsolidated sediment off the marsh surface. Conversely, Ensminger and Nichols (1957) reported that wave action and currents produced during Hurricane Audrey breached levees and removed organic build-up from impoundments on Rockefeller Refuge.

Except during major storm events (tropical storms and hurricanes) that force wind-driven, elevated waters over the impoundment levees, regular flooding with mineral sediment-laden waters does not occur in the impounded marshes (Boumans and Day 1994). Gosselink (1984) reported that for the Delta Plain a wind tide of 1.5 m occurs approximately every 8 yr. Baumann et al. (1984) reported the annual probability of a hurricane passing within 80 km of Barataria Bay is 12%. Regular flooding of the marsh surface has been identified as the self-regulating process by which wetlands counteract submergence (Mitsch and Gosselink 1993). In portions of Louisiana not subject to alluvial sedimentation, sediment delivery to natural coastal marshes is episodic and is provided by storm flood waters (Reed 1989). Although much of the Chenier Plain coastline is currently retreating, Roberts et al. (1989) believe that Atchafalaya River sediments will eventually reverse the process because shore-front sediment deposition from the river is accelerating and moving westward. The natural marsh at unit 15 is near the deposition area and had greater soil bulk density than the natural marsh at units 3 and 14. Based on mineral matter accumulation and soil bulk density in the natural marsh, unit 15 may be a candidate for experimental management of sediment delivery into impounded marshes. Chabreck (1994) recommended use of low levees for construction of impoundments to permit meteorologically elevated waters to overflow levees and allow sediment-ladened waters into impounded marshes with greater frequency. Ensminger and Nichols (1957) documented that levees with good grass coverage exhibited little or no damage during Hurricane Audrey, a condition that would be required if low levees are utilized.

Hatton et al. (1983) and Nyman et al. (1993b) expressed the importance of adequate plant production and the addition of organic materials into the marsh soil to provide a structural matrix for capturing mineral matter and for soil formation. In a Delaware tidal salt marsh, mineral sediment was found to adhere to emergent vegetation and to be delivered later to the marsh soil via washing of the plants by rain or after vegetative senescence at the end of the growing season (Stumpf 1983). Past and present management in the impounded marshes at units 1, 14, and 15 may be assisting an accretionary deficit by increasing organic matter decomposition and soil volume loss during dewatered or drought periods. Impoundment drainage that exposes and drys the soil increases decomposition of organic matter (Nyman and DeLaune 1991) and causes shrinkage of mineral soils (Slusher 1972).

Mean accretion since 1963 and mean marsh surface elevation were lower in the impounded marshes than the natural marshes at units 1, 14, and 15. Excess water is discharged and tidal inflows are regulated in the impounded marshes to meet management objectives, such as dewatering and drying of the marsh soil to produce annual plants (Mouton 1996; Wicker et al. 1983). Between 1963 and 1994, the natural marshes at units 1, 14, and 15 accumulated 67% more mineral matter and 87% more organic matter than the impounded marshes and the elevation of natural marshes increased 6–12 cm more than in the impounded marshes. Inadequate belowground root production and diminished organic matter accumulation may result where annual plant species are the goal of management. Annual plants have limited root systems and aboveground structures may not contribute substantially to organic matter accumulation (Mitsch and Gosselink 1993). Soil drainage increases decomposition (Nyman and DeLaune 1991) thus frequent drainage may oxidize inordinate amounts of soil organic matter (Nyman et al. 1993a). Therefore, dewatering may be encouraging a positive feedback loop, similar to the one proposed by Nyman et al. (1993b), and that may result in less organic matter accumulation and loss of marsh surface elevation in impounded marsh compared to natural marsh.

Mean accretion since 1963 was 56% greater in the impounded marsh than adjacent natural marsh at unit 3. Mean elevation of the impounded marsh in 1963 was 42 cm below the adjacent natural marsh elevation, suggesting that the impounded marsh may have been subject to severe subsidence before 1963. Droughts and forced drainage prior to 1963 may have caused rapid oxidation of unit 3 organic soils. Installation of several water control structures after 1963 permitted shallow permanent flooding, stabilized water levels, increased vegetation growth, and probably caused greater accretion in unit 3. Because of their distance from the Gulf of Mexico, the marshes at Sabine National Wildlife Refuge do not receive significant mineral sedimentation (Paille 1991). The marshes of Sabine National Wildlife Refuge have highly organic soils, and belowground root production may be a major contributor of organic matter (Paille 1991).

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