Peat Collapse, Ponding and Wetland Loss in a Rapidly Submerging Coastal Marsh

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ABSTRACT

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Conversion of coastal marshes to inland open water is often associated with plant stresses such as salt-water intrusion into non-saline marshes and soil waterlogging, but the physical processes that initiate pond formation are not clear. We hypothesized that marsh elevation decreased rapidly following plant mortality because of structural collapse of the living root network. We monitored the elevation of 20 marsh hummocks between April 1990 and April 1992. Near total plant mortality occurred within 1 year and was attributed to excessive flooding. Hummock elevation decreased almost 15 cm within 2 years but elevation of adjacent ponds showed no trend. Plant stubble was still rooted in place on the submerged hummocks, and even slight evidence of surface erosion was not noted until the end of the study. The ^{137}Cs inventory in soil collected before and after the study also indicated that peat collapse rather than erosion caused the elevation decrease. Thus, peat collapse may initiate interior marsh ponds that subsequently spread via erosion and may partly explain why some marshes experiencing plant mortality convert to open water rather than re-vegetate. Peat collapse appeared to be the primary mechanism of marsh loss in this Louisiana hotspot.

ADDITIONAL INDEX WORDS: *Marsh, soil, delta, coast, sedimentation, saltwater intrusion, marsh elevation, marsh loss, and pond initiation, Louisiana.*

INTRODUCTION

Deltaic marshes such as those at the mouths of the Mississippi River in North America and the Nile River in Africa provide an opportunity to study wetland responses to rapid submergence and salt water intrusion, because delta subsidence and river management cause rapid submergence and salt-water intrusion (COLEMAN, 1988; STANLEY and WARNE, 1993). The dominant plant species in the brackish and saline marshes of the Mississippi River Deltaic Plain, *Spartina alterniflora* Loisel. and *Spartina patens* (Aiton) Muhl., are better adapted to flooding with marine water than other plant species but are stressed by these processes none-the-less. Submergence increases flooding and waterlogging, which stresses vegetation and reduces plant production (MENDELSSOHN *et al.*, 1981; CHALMERS *et al.*, 1982; DELAUNE *et al.*, 1983). Salinity also stresses marsh vegetation, particularly the brackish species, *S. patens* (PARRONDO *et al.*, 1978; MORRIS, 1984).

Plant production, primarily root production,

may partly determine the degree of submergence that some marshes can tolerate because some marshes accrete vegetatively via peat accumulation (McCAFFREY and THOMSON, 1980; DELAUNE *et al.*, 1983; BRICKER-URSO *et al.*, 1989; CRAFT *et al.*, 1993; NYMAN *et al.*, 1993a). In the Mississippi River Deltaic Plain experiencing rapid submergence, saltwater intrusion, and wetland loss, NYMAN *et al.* (1993a) concluded that plant stresses caused vertical accretion deficits that in turn increased flooding stress on marsh vegetation. There is, therefore, no equilibrium; instead, flooding increases plant stress that in turn increases flooding, that in turn increases plant stress, *etc.* Such a positive feedback loop cannot persist because flooding will eventually reach 100% and cause total plant death.

The resulting plant mortality might affect marsh surface elevation because the living root network is important in soil structure. Living plant roots form a tightly interwoven network that increases soil strength in upland soils (WALDRON, 1977; WALDRON and DAKESSIAN, 1981; WALDRON and DAKESSIAN, 1982) and apparently in Louisiana and New England marsh soils as well (McCAFFREY

and THOMSON, 1980, personal observation). Organic matter may be particularly important in the structure of many Gulf Coast and Atlantic coast marsh soils because 85% of soil volume is pore space (NYMAN et al., 1990; CRAFT et al., 1993) and the surface of the marsh is not supported by mineral sediments (McCAFFREY and THOMSON, 1980). It is therefore possible that highly organic marsh soils may compact following plant death, initiating new ponds in coastal marshes. Following pond initiation, marsh loss could proceed via erosion as reported elsewhere (STEVENSON et al., 1985; KEARNEY and STEVENSON, 1991; NYMAN et al., 1994). In this paper, we present a study initiated to test the hypothesis that plant mortality caused marsh surface elevation to decrease and hence caused pond initiation and wetland loss. The processes and relationships observed in our study area will likely be applicable to the delta lobe cycle of many deltaic marshes (see COLEMAN, 1988) and may indicate how some coastal and estuarine marshes respond to possible increases in the rate of sea level rise (TITUS, 1986).

STUDY AREA

The study was conducted in part of the Mississippi River Deltaic Plain where marsh loss is extremely rapid (BRITSCH and KEMP, 1990). This site was selected because BRITSCH and KEMP (1990) indicated that it was approximately 200 m from a large shallow water area that was marsh in 1974 (Figure 1). The large shallow water area was a marsh-loss hotspot, which is defined as an area of marsh experiencing rapid conversion to open water that is embedded within a larger area of marsh experiencing a much lower marsh-loss rate (LEIBOWITZ and HILL, 1987). In Louisiana, it is estimated that such hotspots account for only 12% of the land area, but for 43% of the marsh loss (LEIBOWITZ and HILL, 1987).

The study site was classified as brackish marsh in the 1940's and 1950's, but was classified as saline marsh in the 1970's and 1980's (O'NEIL, 1949; USDA, 1956; CHABRECK and LINSCOMBE, 1978, 1988). Conversion of brackish marsh to saline marsh is common in southeast Louisiana and is evidence of salt-water intrusion (CHABRECK and LINSCOMBE, 1982). Salt-water intrusion in this study area is most likely associated with an increasing tidal prism that accompanies the delta lobe cycle (COLEMAN, 1988). In addition to increasing salinity stress on vegetation, salt-water intrusion may also increase the amount of mineral

matter required for soil formation (NYMAN et al., 1990). The soil being created at this study site may have insufficient mineral matter for healthy plant growth (NYMAN et al., 1993a).

In addition to salt-water intrusion, the study site experienced rapid submergence. Tide gauge data collected from 6 tide gauges located within this region of Louisiana indicated that submergence averaged 1.38 cm/yr from the early 1960's to the early 1980's (NYMAN et al., 1993a). Flooding has been shown to stress marsh vegetation and may lead to plant dieback (MENDELSSOHN et al., 1981; DELAUNE et al., 1983b).

Vertical accretion in this general area averaged 0.98 cm/yr between 1963 and 1990 was greater than reported elsewhere (NYMAN et al., 1993a) but inadequate to counter submergence. This accretion deficit would continually increase marsh flooding and plant stress, and a flooding frequency >90% was indicated by data collected by REED et al. (unpublished Open File Report to U.S. Geological Survey, grant no. 14-08-0001-23320). Excessive flooding is believed to be the primary cause of lower plant production occurring in these marshes relative to stable marshes elsewhere in Louisiana (unpublished data in review). Collectively, previous work in this general area suggests that complete plant mortality may occur because of relationships among salt-water intrusion, flooding, inadequate mineral sediments, and vertical accretion.

The marshes in our study area are characterized by hummocks of living S. alterniflora surrounded by shallow water containing rooted stubble, and it appeared that the shallow water areas were recently occupied by living marsh vegetation despite their lower elevation. We suspected that this topography resulted from peat collapse in areas where plant mortality had occurred.

METHODS

Twenty living marsh hummocks within a 50 m by 25 m area adjacent to the hotspot were permanently marked with numbered stakes on 4 March, 1990. The hotspot was approximately 200 meters from our study area at the start of the study. Hummocks varied in size from approximately 1 to 2 m² and the study area had a hummock/water ratio of about 1:7. The number of culms and height of tallest culm was determined in each hummock. Afterwards, Roundup Lawn and Garden Herbicide (Monsanto Co., St. Louis MO, U.S.A. 63167) was applied to each culm in
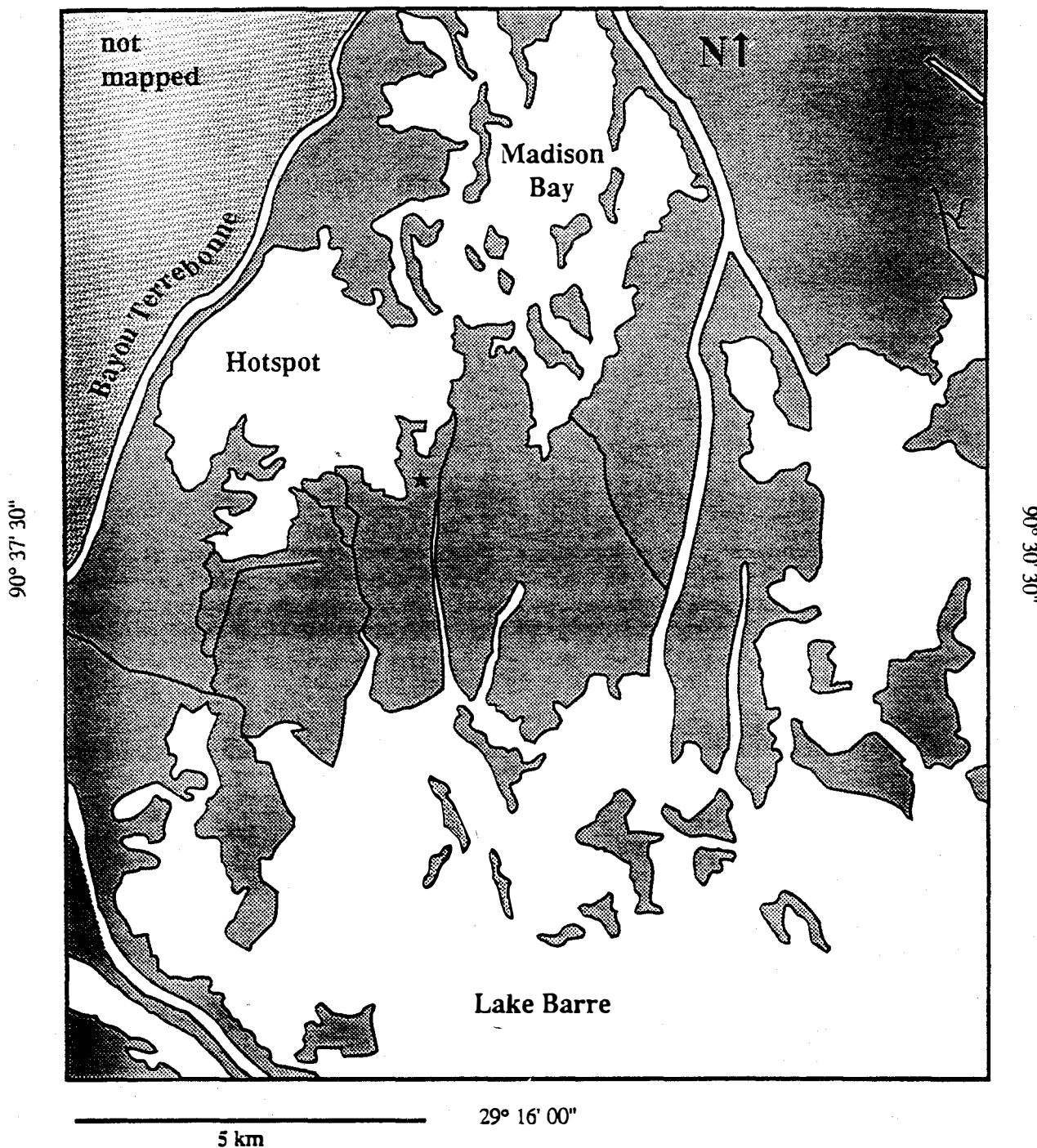
Figure 1. Location of study site where peat collapse was studied.

10 randomly selected hummocks because we anticipated that flooding and plant mortality associated with the spread of the hotspot would occur too slowly for our purposes. Roundup was applied manually to each culm in the treated hummocks with a cotton glove moistened in Roundup, which was worn over a plastic glove to prevent contact with the herbicide. Application in this manner affects only the treated culms and has been used to kill red rice without harming white rice growing in the same pots. All hummocks were visited via pirogue (a small canoe-like boat) to prevent dam-
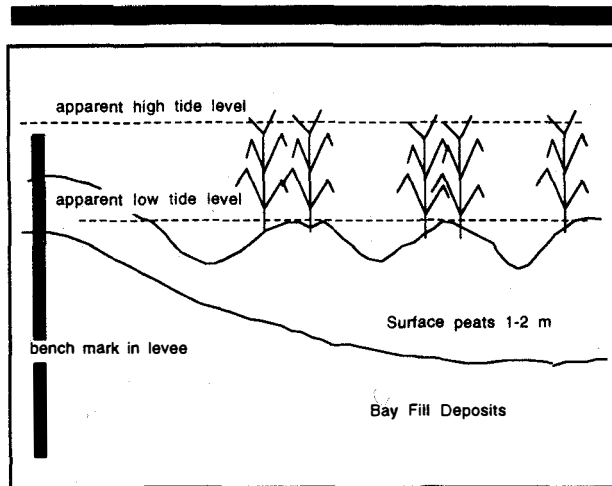
Figure 2.   Representation of levee, pond, hummock, and bench mark elevations at the initiation of field study.

age to marsh soil structure, which was extremely fragile. It was not uncommon to sink knee or even thigh deep when walking in these salt marshes. Use of a pirogue would not be possible in most marshes, but marshes in this area of the Terrebonne Basin are almost continuously flooded.

A bench mark was established on the natural levee of an adjacent, unnamed bayou by inserting an iron pipe (approximately 6-m long) into the ground until only approximately 40 cm remained above ground (Figure 2). Elevation of each hummock and adjacent pond bottom was determined relative to the bench mark on 4 March 1990 with a transit level prior to treatment with herbicide. Hummock elevations were determined on the north side of the marker stake approximately 5 centimeters from the stake. Pond bottoms were surveyed adjacent to each hummock. Levee elevation was also determined. Levee stations were 3 meters apart from one another starting at the bench mark and running along the crest of the natural levee. Five stations were east of the bench mark and 5 were west of the bench mark.

The permanent bench mark and permanently marked sample sites provided a system for measuring changes in surface elevation relative to the upper 6 meters of deposits but independent of deeper subsidence and compaction. The sedimentation-erosion table described by BOUMANS and DAY (1993) works on the same principle. The bench mark and permanent stations allowed a greater surface area of marsh to be sampled (1,250 m² vs. 4 m²), but with a lower precision than the sedimentation-erosion table (0.5 cm vs. 0.05 cm).

Elevation and vegetation data were collected again on 14 August 1990 (day 163), 15 March 1991 (day 385), 1 August 1991 (day 504), and 1 April 1992 (day 750) although levee elevation was not determined on 14 August 1990. Pond and levee stations were marked with their own stakes on 1 August 1991 to further increase precision of those estimates. Initial design called for comparing the elevation of living and dead hummocks over time, but the hotspot spread faster than expected. Within 1 year open water had almost completely replaced vegetated marsh in this study site and for hundreds of meters around as the adjacent hotspot spread across the study site and beyond. Sampling was terminated 1 April 1992 after the marker stakes were vandalized.

Vertical accretion since 1963 was estimated with ^{137}Cs dating (DeLaune et al., 1978) in 2 cores collected from within the study area in February 1990 and April 1992. Each core was collected from a different hummock. Hummocks that provided cores in 1990 were not sampled again because they were destroyed during core collection; the hummocks sampled in 1992 were permanently marked hummocks monitored throughout the study. The change in ^{137}Cs inventory between the 1963 horizon and marsh surface was compared between cores collected at the beginning of the study, before marsh loss occurred, to cores collected at the end of the study, after marsh converted to open water, to determine the relative importance of erosion and peat collapse.

We originally intended to test our hypothesis regarding the effect of plant mortality on marsh surface elevation by comparing the elevation of treated (dead) and untreated (living) hummocks over time. This was not possible because the hotspot spread across our study area the summer following the start of data collection, which caused all hummocks to die. We therefore compared changes in elevation over time among hummocks, pond bottoms, and levee stations to test the hypothesis that death of emergent marsh vegetation caused marsh elevation to decline. Proc GLM of SAS (SAS Institute Inc., Cary, NC U.S.A. 27512) was used to test the hypothesis that elevations did not change differently among hummocks, ponds, and levee elevations stations. For this analysis, data were analyzed as a repeated measures testing for a significant time by station type interaction. Proc REG of SAS (SAS Institute Inc., Cary, NC U.S.A. 27512) was used to test for linear relationships between elevation and time.

RESULTS

Stem density averaged 64 stems per hummock at the start of the study. Plant mortality was total in the treated hummocks by August 1990. Untreated hummocks experienced rapid mortality as well and stem density averaged less than one by March 1991. No plants were living by August of that year. As noted, plant mortality was widespread for hundreds of meters to the south of the study area as the adjacent hotspot spread across the study area in 1990. Stem density on the natural levee also appeared to decline drastically throughout the study, but quantitative data were not collected.

At the beginning of the study, the hummocks averaged 10.2 cm lower than the crest of the natural levee; pond bottoms averaged 31.2 cm lower than the hummocks. Statistical analyses indicated that elevation changed differently over time among hummock, pond, and levee stations (P = 0.0001, 2 and 215 df, F = 12.36). Thus, the three station types were analyzed individually in the subsequent regression analyses. Hummock elevation decreased almost 15 cm throughout the study period (Figure 3). Regression analyses indicated a significant linear change of -7.1 ± 0.8 cm/yr (T = -8.336, 1 and 89 df; P = 0.0001). Levee elevation also decreased over time (Figure 3), but the decline was only -3.1 ± 0.6 cm/yr (T = -5.486, 1 and 38 df, P = 0.0001). There was no significant linear change in elevation of the pond bottoms (T = -1.361, 1 and 89 df, P = 0.1770), but they appeared to be increasing in elevation in the second year of the study (Figure 3).

Hummock elevation appeared to decrease more during the summers than during the winters (Figure 3). No evidence of surface erosion was noted until April 1992, the final sampling date, even though a significant decrease in elevation was apparent as early as August 1990. Fine roots were exposed at the base of some dead culms on the final sampling date, which gave the appearance that 2–3 cm of soil had eroded from the surface of some hummocks. Thus, we suspect that this surface erosion had occurred primarily during the preceding winter. We did not note any evidence of lateral erosion, either before, during, or after the hotspot spread across the study area.

Data from the cores collected before and after the study were inconclusive regarding the peat collapse hypothesis. No difference was noted in bulk density between soil collected before and after plant death, which suggested either surface
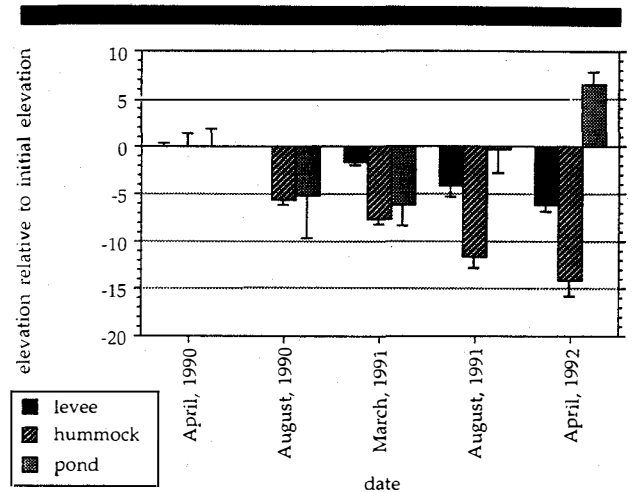

Figure 3. Changes in elevation in levee and hummock stations observed during the two year study.

erosion or rapid decomposition of soil organic matter. Unfortunately, the cores were inadvertently discarded before organic matter content were determined. However, the ^{137}Cs profile in cores taken before and at the completion of the study were consistent with the peat collapse hypotheses. The depth of the 1963 marker horizon averaged 34.5 cm prior to marsh loss, but 25.5 cm after marsh loss, for a 9 cm difference (Figure 4). Even though elevation above the 1963 marker horizon had decreased 26% between the beginning and end of the study, the ^{137}Cs activity above the 1963 marker horizon was only 5% lower at the end of the study. ^{137}Cs activity above the 1963 marker horizon averaged 1,101 counts per hour in cores taken before the study began. The upper 9 cm of soil contained 24% of this activity, or 264 counts per hour. However, ^{137}Cs activity above the 1963 marker horizon in cores collected at the completion of the field study averaged 1,045 counts per hour, which was almost as great as that in the previously collected cores. If the loss in elevation had resulted from erosion, then the ^{137}Cs activity above the 1963 marker should have been reduced approximately 24%.

Thus, the observed decreases in elevation apparently did not result from the erosion of surface sediments but rather from the collapse of the living root network in the surface peats after plant mortality occurred. This collapse is also evident in the apparent increase in ^{137}Cs concentration in the upper 30 cm of soil between the beginning and end of the study (Figure 4).
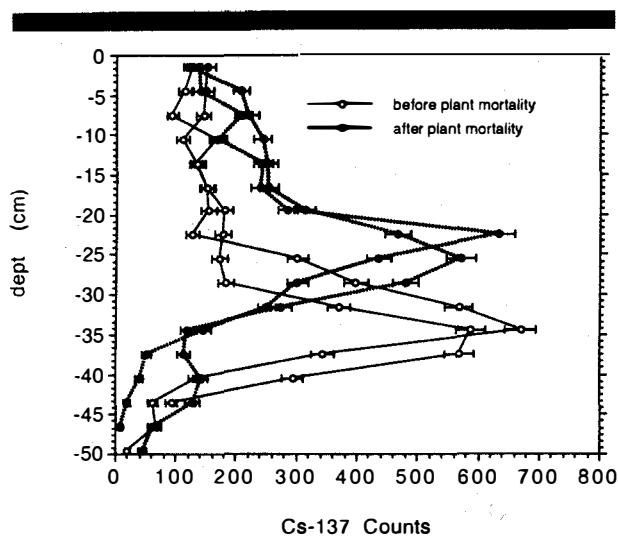
Figure 4. ¹³⁷Cs profiles with depth in cores collected at the initiation of field work and two years later at the completion of field work.

DISCUSSION

The widespread decline of marsh vegetation was attributed primarily to flooding. Flooding and associated stresses are known to stress S. alterniflora (GOOD et al., 1982) and can lead to plant mortality (MENDELSSOHN et al., 1981; DELAUNE et al., 1983b). Almost continuous flooding was indicated at the end of the study by the presence of oysters growing on marker stakes and even near the top of our bench mark on the natural levee. These oysters grew to >7 cm long on the marker stakes and >5 cm long on the bench mark by the end of our field work. The presence of oysters growing >25 cm above the elevation of the natural levee indicated that even these natural levee areas were excessively flooded. No oysters were noted in ponds. This was attributed to a lack of attachment surfaces on the extremely soft bottom. The accumulation of soft sediments in the pond bottoms may have been responsible for the increase in pond bottom elevation indicated in the second year of the study.

Data collected in this study strongly suggested the occurrence of peat collapse. Hummocks lost elevation even though adjacent pond bottoms appeared to be accumulating sediments. No evidence of erosion was noted despite elevation losses, and the ¹³⁷Cs inventory was virtually unchanged following elevation loss. Elevation losses were greater in the hummocks, where plant mortality and soil organic matter content were greater, than

on the levee where vegetation persisted and soil organic matter content is less. These observations strongly suggest that the surface was compressed rather than removed via erosion. Compaction of surface peats has not previously been reported, but these soils are highly porous and organic (NYMAN et al., 1990). These are characteristics associated with sediment compaction that occurs via dewatering and degassing that is common in deltaic deposits (FRAZIER, 1967; COLEMAN, 1988). Additional tests of the peat collapse hypothesis are needed because the initial experimental design was destroyed by the rapid spread of the hotspot, and it was not possible to determine organic matter content in cores collected at the end of the experiment.

Peat collapse rather than erosion appeared to be the mechanism by which marsh converted to open water throughout the hotspot. No evidence of surface erosion was noted until long after the hummocks lost elevation. Small sub-aqueous mounds, some with decaying S. alterniflora stubble, were observed in the hotspot south of the study site where marsh loss occurred simultaneously with that in our study area. The hummocks monitored in this study took on the appearance of those mounds after plant mortality and peat collapse. This was quite different from marsh loss that we observed at another location in Louisiana (NYMAN et al., 1994).

Peat collapse following plant death could originate from an increase in the decomposition rate of root tissue, from a loss of root turgor, or from a combination of these two processes. Following death, perhaps root tissue was rapidly colonized by Clavatospora bulbosa, a filamentous fungus. This fungus may rapidly decompose soil organic matter in salt marshes by transporting oxygen downward through hyphae so that decomposition proceeds aerobically (PADGETT et al., 1989; PADGETT and CELIO, 1990). However, this might not be important because HACKNEY (1987) noted that decomposition might actually slow following plant death; he also noted no difference in decomposition rates between areas with and without filamentous fungi. Another possible mechanism for peat collapse is the loss of turgor by root tissue following death. Spartina alterniflora has a relatively dense root network (BELLIS and GAITHER, 1985). The roots contain a series of lacunae that form a continuous gas filled aerenchyma system and occupy a significant amount of root volume. ARENOVSKI and HOWES (1992) found that lacunae

occupied 29% of root cross sectional area in live turgid *S. alterniflora* roots. Porosity is even greater, up to 35%, in *S. patens* (KLUDZE and DE-LAUNE, in press). Perhaps the loss of turgor by thousands of tiny roots, each with it's own lacunae contribute to peat collapse as shown in Figure 5. Regardless of the mechanism, peat collapse is possible only in highly organic marsh soils such as those on the Gulf of Mexico coast and the New England Atlantic coast where the marsh surface is not supported by mineral sediments (*e.g.,* McCAFFREY and THOMSON, 1980).

Any factors that cause plant mortality may contribute to peat collapse. In our study area, *S. alterniflora* growth may have been adversely affected by low soil mineral matter content and excessive flooding. Herbivory by nutria (*Myocastor corpus*) and muskrats (*Ondatra zibethicus*) appeared to be extremely heavy during 1990 and may also have contributed to plant stress in our study area. Density of muskrat houses averaged roughly 1/300 m² in marsh within 20 meters of bayous in 1989 and 1990, but only a single muskrat house was noted along 15 km of shoreline visited in March of 1991 (J.A. NYMAN, unpublished data). Herbivore populations appeared to crash during the winter of 1990–1991 when there was very little *S. alterniflora,* which they eat. Herbivores did not appear common since then, and vegetation recovered in nearby areas where peat collapse did not occur.

Peat collapse might explain why some brackish marshes convert to open water rather than to salt marsh during salt-water intrusion (*e.g.,* SASSER *et al.,* 1986). If *S. alterniflora* does not establish an extensive root network in *S. patens* marsh before *S. patens* is killed by salinity or flooding, then surface peats in brackish marshes might collapse following mortality of *S. patens.* Colonization by *S. alterniflora* would not be likely following peat collapse, because the areas would convert to interior marsh depressions that are likely to flood excessively with rain or tidal water.

CONCLUSIONS

Wetland loss is the result of many interacting factors, but geological factors appear to be the underlying cause for a majority of the loss in coastal Louisiana. The Louisiana coast has undergone change for thousands of years because of the delta lobe cycle in the Mississippi River (COLEMAN, 1988). The river rapidly filled bays allowing marsh vegetation to establish. Over the following cen-
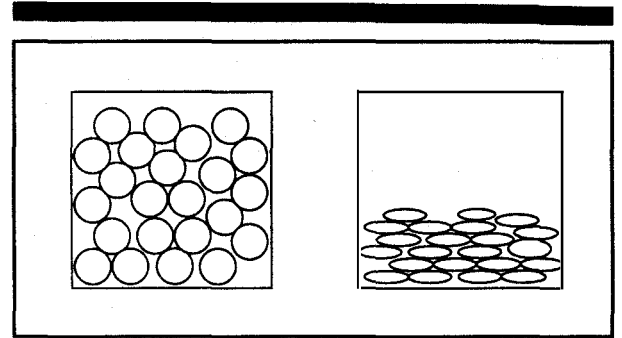

Figure 5. Living plant roots are turgid and contain significant air passages (A). Loss of turgor following plant death may contribute to peat collapse because the large air spaces inside plant roots may collapse (B).

turies, original sediments consolidated and subsided, but marsh continued to exist because peat accumulated on the marsh surface. The original sediments are still consolidating, which combines with global sea level rise to produce submergence rates that exceed 1 cm/yr in some areas of Louisiana (PENLAND and RAMSEY, 1990). The underlying geological processes therefore dominate marsh surface-water surface relationships, but this is of little consequence when the river supplies adequate sediments and fresh water to marshes for soil formation. Fresh water is important because fresh marshes require less mineral sediments than salt marshes to vertically accrete (NYMAN *et al.,* 1990). Because of delta switching and levying of the Mississippi River, many marshes such as in the Terrebonne Basin are sediment and freshwater deficient. In such rapidly subsiding environments, continued existence of marsh habitats is dependent on the ability of the marsh to maintain its elevation within the tidal range through vertical accretion (DeLAUNE *et al.,* 1978; DeLAUNE *et al.,* 1983). Accretion is accomplished through mineral sediment and peat accumulation. However, there is a critical mineral sediment requirement for maintenance of salt marshes; salt marshes with soil bulk density of less than 0.2 g cm^{-3} will not support plant growth (DeLAUNE *et al.,* 1979). For sediment deficient environments such as the Terrebonne Basin marshes, there is not enough mineral sediments, given the submergence rate and salinity level, to support vegetative growth and marsh surface elevation. As a result, vertical accretion does not keep pace with submergence. The resultant increase in submergence stresses plant communities and reduces
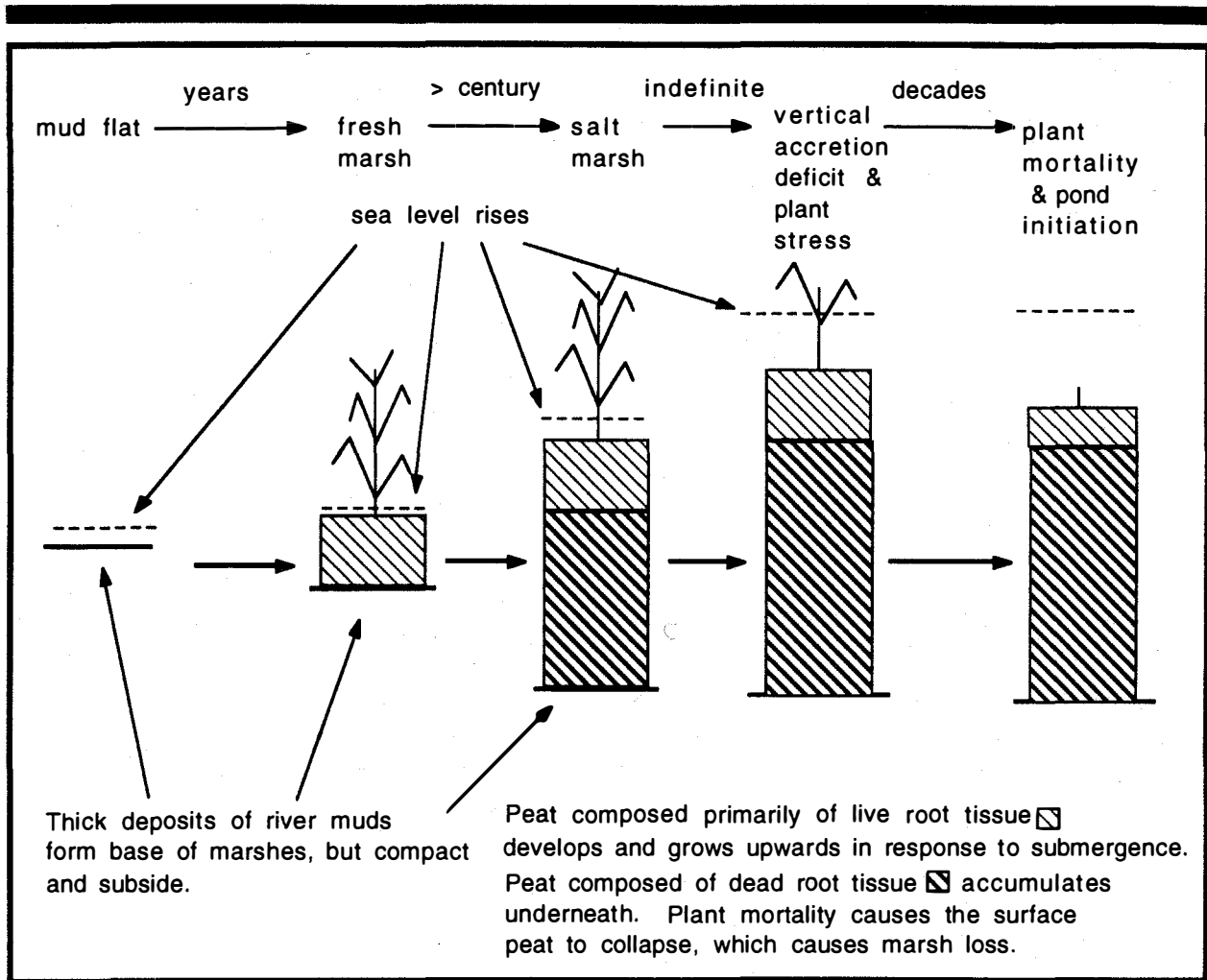
Figure 6.   Schematic view of hypothetical processes involved in marsh building, marsh maintenance, and marsh ponding.

plant productivity, the source of soil organic matter that directly determines vertical accretion (McCAFFREY and THOMSON, 1980; DeLAUNE et al., 1983; BRICKER-URSO et al., 1989; CRAFT et al., 1993; NYMAN et al., 1993). After several decades of inadequate vertical accretion, a critical point is reached in the accretionary process in which plant mortality and peat collapse occurs (Figure 6).

ACKNOWLEDGEMENTS

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□ RESUMEN □

Este artículo presenta resultados de 3 estudios llevados a cabo en una región del llano deltaíco del Río Mississippi, el cual esta sujeto a condiciones similares causadas por el efecto de invernadero como son un hundimiento rápido del sedimento e invasión de agua salada. Un estudio inicial indicó que el incremento vertical del sedimento depende directamente de la acumulación de materia orgánica, y que la importancia principal de los sedimentos minerales fue como nutrientes para las plantas. El incremento vertical fue rápido pero el hundimiento fue mayor. Esto aparentemente causó una retroalimentación positiva en donde la inundación excesiva limitó la producción vegetal, la cual, a su vez, limitó el incremento vertical de los sedimentos; ésto resulto en una mortalidad vegetal. En otro estudio se encontró que la producción vegetal fue menor cuando la invasión de agua salada era más avanzada e indicó que la vegetación en ambientes salinos no estaba reemplazando la vegetación salobre, tal vez debido a los bajo niveles de materia mineral de los sedimentos. La baja productividad limitó la cantidad de materia orgánica para el incremento vertical y exportación hacia las aguas estuarinas adyacentes. Así, el hundimiento y la invasión de aguas saladas pueden causar una mortalidad vegetal cuando esos factores ocurren rapidamente y los sedimentos minerales son inadecuados.

Para nuestro estudio final se hipotetizó que la elevación de los pantanos disminuiría rápidamente después de una mortalidad de las plantas debido al colapso estructural de las raíces. Medimos la elevación de 20 parcelas en un pantano entre Abril 1990 y Abril 1992. La mortalidad vegetal fue casi completa dentro de el período de un año y se atribuyó a la inundación excesiva. La elevación de las parcelas bajó casi 15 cm dentro de un periódo de 2 años, pero la elevación de las charcas contiguas no mostró ninguna tendencia. Tallos secos con sus raices permanecieron intactos en las parcelas ya sumergidas, y más aún, no se observo erosión superficial sino hasta el final del estudio. El inventario de ^{137}Cs en los sedimentos colectados antes y después del estudio tambien indicó que el colapso de la turba y no la erosión causó la disminución de la elevación. Así, el hundimiento de la turba pueda iniciar la formación de charcas interiores en el pantano, y posteriormente extenderse debido a la erosión; esto explica parcialmente porqué algunos pantanos con mortalidad vegetal son convertidos a charcas mas que iniciar una revegetación.