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# Mid-Texas Coastal Marsh Change (1939–1991) as Influenced by Lesser Snow Goose Herbivory

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**ABSTRACT**

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Emergent coastal marshes of the San Bernard National Wildlife Refuge (SBNWR), were evaluated from 1939 to 1991 using aerial photography and a geographic information system (GIS). Vegetated marsh was transformed to mudflats and open water in areas heavily utilized by wintering lesser snow geese (LSG). Unvegetated marsh increased from less than 4% in 1939 to 21% in 1991. Rate of denudation increased after 1965 when LSG numbers of 300,000 in the 1950's increased to nearly 1,000,000 by the 1970's. Over time, some mudflats have revegetated, while others have become deep, open-water areas. Extremes of inter- and intra-annual tide levels, surface water and interstitial soil water salinity, and precipitation were also experienced during this time period. Repeated and intense herbivory by LSG followed by frequent tidal inundation, high soil and water salinities and extended droughts results in vegetation loss and the potential for accelerated soil erosion.

**ADDITIONAL INDEX WORDS:** *Disturbance, landscape pattern dynamics, patch dynamics, fire, cattle herbivory, lesser snow geese, wetland vegetation loss, GIS.*

## INTRODUCTION

Loss and alteration of Gulf Coast marshes have been extensive since the time of settlement (TINER, 1984; DAHL, 1990). Where marshes have not been totally eliminated or altered by man, there has often been a shift from emergent vegetation to mudflats and open water (WHITE *et al.*, 1993). As a result, overall habitat is changed and potential for further alteration through erosion and reduced sedimentation may exist. This shift within coastal marsh landscapes has been attributed to a variety of interacting biotic and abiotic factors that operate at various temporal and spatial scales. Land subsidence, sea level rise, weather events, alteration of fresh and saline water inflows, and herbivory, as well as synergistic effects of these disturbance agents, may influence marsh landscape change (LYNCH *et al.*, 1947; SALINAS *et al.*, 1986; TURNER and CAHOON, 1987; MENDELSSOHN and MCKEE, 1988; KERBES *et al.*, 1990).

The most notable herbivores implicated in marsh alteration are snow geese, muskrats and nutria (LYNCH *et al.*, 1947; JEFFERIES *et al.*, 1979; FULLER *et al.*, 1985; KERBES *et al.*, 1990; MEEDER and PERRY, 1990). Lesser snow geese (LSG) often uproot vegetation, consume roots and rhizomes, and discard stems and crown material (LYNCH *et al.*, 1947). LSG have been identified as agents for replacement of vegetation by mudflat and open water in the western Hudson Bay Canada and Louisiana (LYNCH *et al.*, 1947; KERBES *et al.*, 1990; MEEDER and PERRY, 1990; IACOBELLI and JEFFERIES, 1991; MILLER, 1993). More birds and reduced revegetation, as a result of environmental constraints, have increased the magnitude and rates at which vegetated areas are converted to mudflats and open water in Canadian and mid-Texas coastal marshes.

Communities may be relatively stable and resistant to disturbances associated with herbivory up to certain thresholds (ARCHER and SMEINS, 1991). However, beyond those thresholds, changes may be rapid, intensified and perhaps irreversible if influenced by additional disturbances such as extreme weather events. Recovery of sites where seed germination is uncommon is controlled by

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reestablishment from plant fragments as constrained by subsequent environmental conditions (CHOU *et al.*, 1992; MILLER, 1993).

Development of mudflat/open water areas was observed on the San Bernard National Wildlife Refuge (SBNWR) in areas heavily utilized by LSG during the 1970's and 1980's. Numbers of geese in Texas increased from 300,000 in the mid 1950's to 1,000,000 in the mid-1970's and 700,000–800,000 in the 1980's (HASKINS, 1992). Prescribed burning and cattle grazing were additional disturbance agents. In addition during this period considerable variation in water level and salinity occurred in association with El Nino and La Nina events and with tropical storm and hurricane activity (CHILDERS *et al.*, 1990).

It was hypothesized that disturbance mediated vegetation alteration and mudflat/open water area increases have accelerated within the coastal marsh landscape on the SBNWR over the past 50 years. Specific objectives of this study were: (1) to utilize historical aerial photography to quantify the vegetation/mudflat/open water pattern of change within the SBNWR salt marsh from 1939 to 1991, and (2) to identify and describe variations in abiotic and biotic disturbance agents which may be related to these changes.

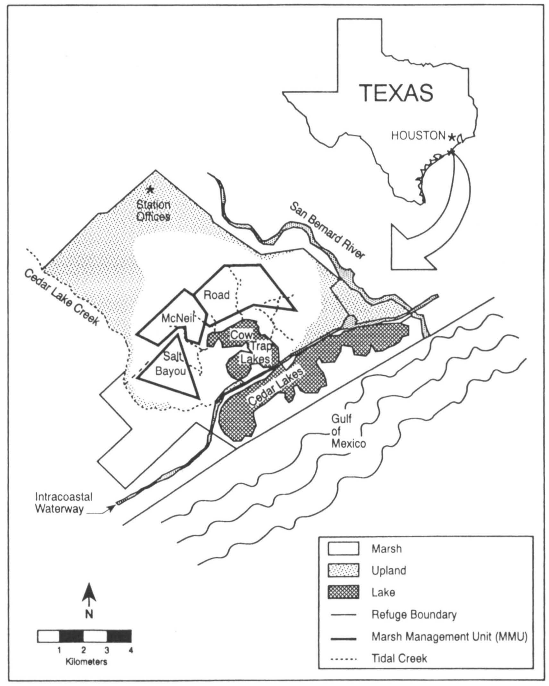


Figure 1. Location and features of the San Bernard National Wildlife Refuge.

## STUDY AREA

San Bernard National Wildlife Refuge is located in Brazoria County, Texas, approximately 110 km southwest of Houston, Texas (28°55′N, 95°35′W) (Figure 1). The 10,000-ha refuge was established in 1968 to provide feeding and roosting habitat for 20,000 to 100,000 wintering LSG. The refuge consists of a natural coastal marsh basin which is flat to slightly concave, with elevational differences of from −1 (bottom of Cow Trap Lake) to 2 m above mean sea level. The marsh overlies Modern-Holocene deltaic deposits of the relict Brazos-Colorado delta (WHITE *et al.*, 1988). Predominant soils are the Harris soil series, which is classified as a fine, montmorillonitic, thermic Typic Haplaquoll (NATIONAL COOPERATIVE SOIL SURVEY, 1981).

The area is characterized by a subhumid marine type climate (THORNTHWAITE, 1948), a 268-day growing season, and average annual rainfall on the refuge of 130 cm (1976–1990) and 127 cm (1938–1990) at Freeport, Texas, which is located approximately 16 km east of the refuge (Figure 2a). Rainfall peaks occur in late spring/early summer and early fall to mid-winter; summers can be droughty. Annual precipitation is highly variable with several years of low precipitation typically broken by several years of above normal rainfall. Increased water deficit causes increased average and extreme salinities in the bay-estuary-lagoon system (WHITE *et al.*, 1988) (Figure 2b).

Water exchange within the basin originally occurred through two small outlets: from Cedar Lake Creek into the Gulf of Mexico and from Cedar Lake into the San Bernard River (Figure 1). Development of the Gulf Intracoastal Waterway (GIWW) in 1917 and 1942 increased saline water intrusion and tidal variation. This, along with altered overland runoff and natural variation in precipitation and evaporation, is believed to have caused a general increase in salinity.

Daily lunar tides exhibit a mean range of 0.2 m (1989–1990, refuge records). Water levels are highest in spring and fall and lowest in winter and summer. Tropical storms and hurricanes periodically produce above normal tides. Inter-annual sea level variation generally reflects variation in annual precipitation (Figure 3).

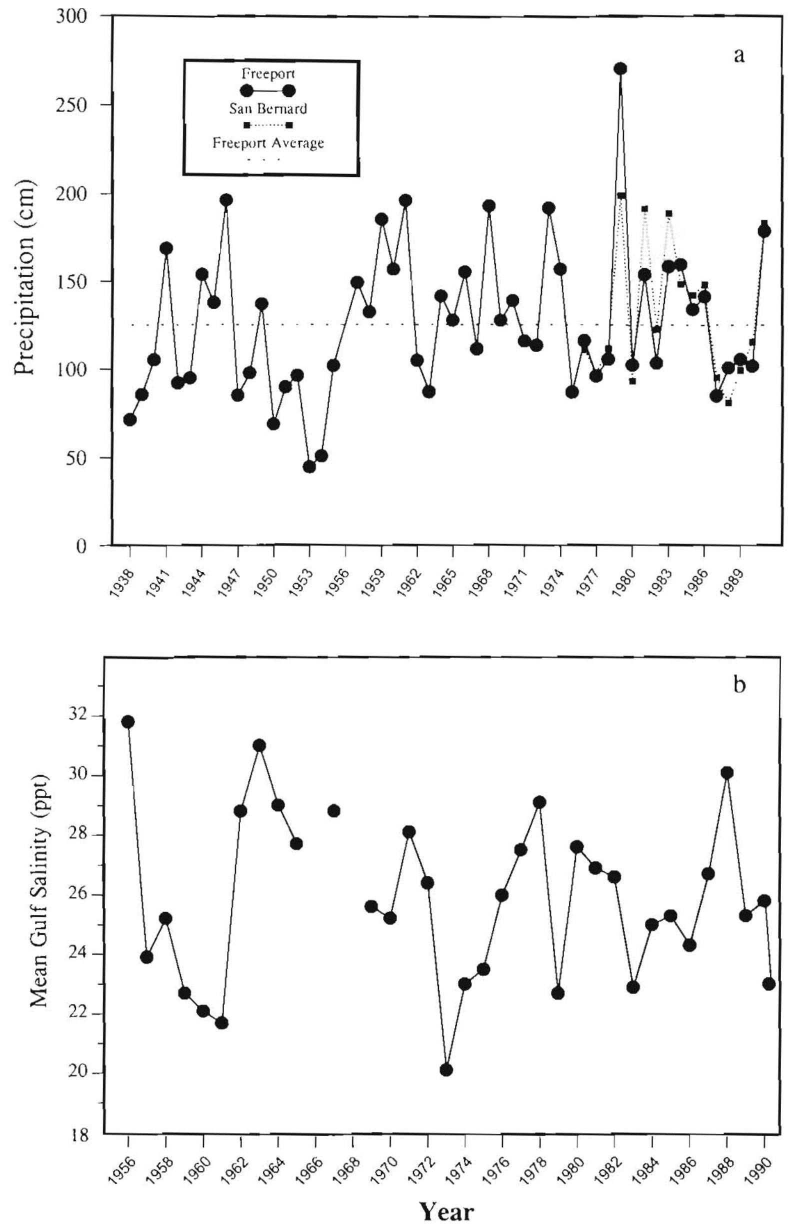


Figure 2. (a) Total yearly and long-term average precipitation (cm) recorded at Freeport, Texas (1938–1991) and total yearly precipitation at the SBNWR (1979–1991), and (b) mean yearly gulf salinity recorded at Freeport, Texas (1956–1991).

Vegetation varies along a decreasing salinity/tidal influence gradient. The area immediately adjacent to Cow Trap Lake consists of regularly flooded emergent marsh interspersed with tidal creeks and ponds and is dominated by *Spartina alterniflora* Loisel. (smooth cordgrass)[1]. Irregularly, flooded emergent marsh occurs inland from

[1] Nomenclature follows *Checklist of the Vascular Plants of Texas* (HATCH *et al.*, 1990).

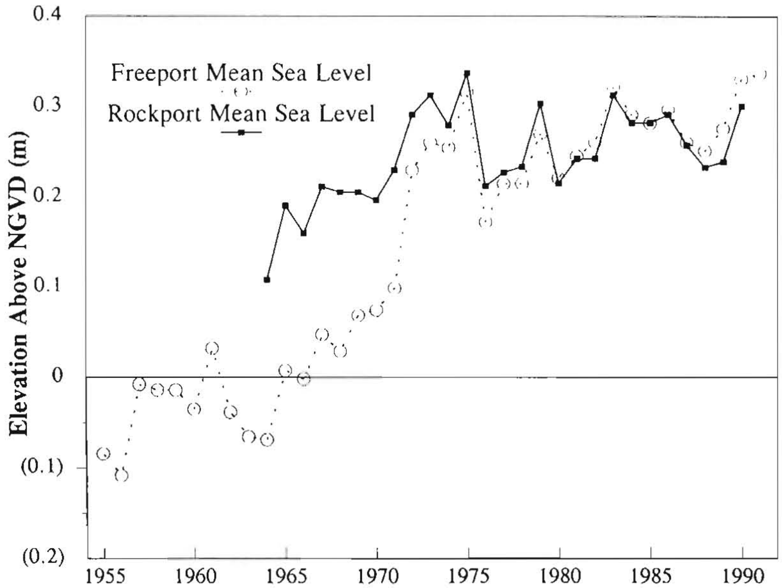


Figure 3. Mean annual sea level adjusted to national geodetic vertical datum of 1929 (NGVD) recorded at Freeport, Texas, and Rockport, Texas. The tide gauge at Freeport has experienced accelerated subsidence in association with local ground water extraction. Installation of flood gates may have also altered the gauge readings. However, the secular variation noted from 1970–1990 is similar to that noted at more stable tide gauges located at Rockport and other locations along the Texas coast (National Oceanic and Atmospheric Administration).

this zone and consists of three major plant communities. Areas frequently flooded by tide water are currently dominated by *Distichlis spicata* (L.) Greene (saltgrass), *Salicornia virginica* (L.) (Virginia glasswort) and *Spartina alterniflora*. Areas less frequently influenced by tide water are dominated by *Spartina patens* (Ait.) Muhl. (marshhay cordgrass) or a mosaic of *S. patens, D. spicata, Paspalum vaginatum* Sw. (seashore paspalum), *Scirpus americanus* E.G. (Olney bulrush) and *Scirpus robustus* Pursh (salt-marsh bulrush). Localized water depth, recent water levels and salinities, cattle grazing history, LSG herbivory and burning determine the relative abundance of these species (CHABRECK, 1988). Still less tidally influenced areas are dominated by *S. americanus/P. vaginatum* which receive tide water only in association with seasonally high tides and tropical storms. Landward from this zone at high elevations and rarely influenced by tides is a *Spartina spartinae* (Trin.) Merr. (Gulf cordgrass) zone that merges with upland prairie.

Following establishment of SBNWR in 1968, historical management practices utilized since the turn of the century were continued until the mid-1970's. These practices included annual late summer/early fall burning and year-long uncontrolled cattle grazing at approximately 11,000–13,000 animal unit months (AUM's) on the 10,000 ha. In 1975, the burning season was changed from summer to late fall/early winter with a 3- to 5-year or more rotation. A grazing regime was adopted that essentially restricted cattle to the marsh and adjacent *Spartina spartinae* dominated areas from October to mid-April.

Grazing complemented the burning program so that *S. patens* and *S. spartinae* could be suppressed and *D. spicata, S. robustus, S. americanus* and *Eleocharis* spp., which are preferred waterfowl food plants (CHABRECK, 1988), would be increased in relative abundance. Grazing pressure was controlled by fence rehabilitation. AUM's were reduced to 7,550 AUM in 1975 with a deferred rotation grazing plan implemented (JIM NEVILLE, U.S. Fish and Wildlife Service biologist, *personal communication*). Further reduction to 4,000–5,000 AUM's occurred during the 1980's with cattle moving, sometimes freely, between fenced grazing units. Grazing on the majority of the refuge was discontinued after the winter of 1988 because of drought.

## METHODS

Historical aerial photographs of the SBNWR were obtained from the Texas Natural Resource Information System, the Army Corps of Engineers, the Texas Department of Transportation, the United States Fish and Wildlife Service, and the Environmental Protection Agency. Black and white and color infrared photography at scales varying from 1:16,000 to 1:56,000 were available for 12 dates from 1939 to 1991. Analysis was restricted to the irregularly flooded marsh. It was nearly continuously vegetated in 1939 and has been utilized by wintering LSG for feeding and roosting throughout the refuge's history. The area analyzed contained portions of three marsh management units (MMU) (Salt Bayou, McNeil and Road), and a small section of a fourth unit (Riverbend). Riverbend is adjacent to Road MMU and will be included in Road MMU for the analysis (Figure 1). All three major plant communities in Road MMU were consistently covered by aerial photography; however, the *S. americanus/P. vaginatum* community type was not always covered for McNeil and Salt Bayou MMU's, and hence only two community types were included for these units. Total area analyzed was 386 ha, 417.7 ha, and 810.5 ha for Salt Bayou, McNeil and Road/Riverbend MMU, respectively. Each management unit was surrounded by a perimeter fence and was influenced by a different tidal creek. Each experienced a different and poorly documented history of LSG herbivory, cattle grazing and burning.

The smallest unvegetated area that could be consistently traced on the photographs was 50 $m^2$. Smaller unvegetated areas could be identified but not accurately traced. Four land type categories were recognized: (1) vegetated marsh = continuous canopy of emergent vegetation, (2) sparsely vegetated marsh = numerous small unvegetated patches up to 50 $m^2$, (3) mudflats = denuded of emergent vegetation except for vegetation remnants of less than 2 to 16 $m^2$ with gaps of 50 $m^2$ or more, and (4) water/mudflats = also denuded with depressed elevation and standing water (except during prolonged droughts). Ground reconnaissance indicated that mudflat areas were often completely or partially covered by an algae mat and had roots and stems of uprooted vegetation incorporated in the upper 50 cm of sediment (litter/sediment layer). Water/mudflats had depressed elevation because of litter/sediment layer loss.

The mudflat category changed to sparse vegetation when mudflats and water/mudflat areas were partially revegetated by remnant vegetation patch expansion, so that openings for the most part became smaller than 50 $m^2$ (openings interspersed with vegetation). Errors in categorizing an area as mudflat or water/mudflat may result from variations in tide level, rainfall and photographic scale. Therefore, the most accurate values resulted from summation of the mudflat and water/mudflat categories, with the resultant category referred to as unvegetated. Although less accurate, additional information could be inferred from further separation of the landscape into mudflat and open water/mudflat categories. Errors were small since elevation differences between mudflat and open water/mudflat categories appeared to be distinguishable in most years, regardless of water level.

The available photographs did not adequately cover all MMU's in all years. For each year and MMU covered, area of individual categories was entered into a Geographic Information System (GIS) (Arcinfo) (LUDEKE *et al.*, 1990) by tracing the outline of each area onto mylar sheets and manually digitizing. Spatial extent of each category was determined and mapped.

Anecdotal information concerning LSG numbers and their feeding habits, marsh burning, cattle grazing, tide levels, and precipitation was gathered. Information sources included SBNWR monthly activity reports, yearly narrative reports, stocking rate and proper grazing use records, goose-use surveys, prescribed burning records, USFWS biologist trip report and personal communication with refuge personnel. Quantitative data available included LSG numbers determined by USFWS monthly winter aerial waterfowl surveys (1974–1991) (HASKINS, 1992). Hourly water levels monitored on the refuge in 1989 and 1990 only were compared to values at Freeport. While the absolute values varied by 0.24 m, the two gauges tracked each other closely. Therefore, long-term water levels measured at Freeport should reflect relative water levels on the refuge. Precipitation data was available from refuge records for 1975–1991. Additional tide level and precipitation data for Freeport and Rockport stations were obtained from National Oceanic and Atmospheric Administration.

## RESULTS

### Change in Amount of Vegetated Emergent Marsh

Ninety-five percent or more of the three MMU's was continuously vegetated with emergent marsh vegetation in 1939 (Figures 4, 5, 6 and 7). Sparsely vegetated extent was less than 4% for each MMU. Composition of the vegetation is unknown. The largest continuous unvegetated areas (mudflat or water/mudflat category) were 4 ha, 1 ha and 7.3 ha for Salt Bayou, McNeil, and Road/Riverbend MMU, respectively. No additional unvegetated sites were noted in 1958 photography.

Unvegetated (mudflat plus water/mudflat) area for the 1,600 ha analyzed increased <2% from 1939 to 1961–1965; while from 1961–1965 to 1991, unvegetated area increased 17%. Vegetation loss began to increase in the early- to mid-1970's, and this trend has continued (Figures 4, 5, 6 and 7). Some denuded areas appeared and later were revegetated, while new denuded areas were simultaneously created. However, in all units, the largest and most recently (since 1970) produced mudflats (with the exception of the southeastern section of McNeil pasture) and water/mudflat areas continued to grow larger through time or experienced minimal decline.

The greatest increase in unvegetated area for Salt Bayou MMU occurred from 1972 to 1977 (Figure 4, Table 1). Because of litter/sediment layer loss which resulted in conversion of mudflats to water/mudflats, water/mudflat area increased from 1977 to 1983 and mudflat area declined (Figure 7). Water/mudflat area continued to increase to a 1987 maximum. Fluctuations of 2% to 5% in unvegetated extent from 1977 to 1991 may be real or may result from delineation error due to differences in aerial photography scales and quality, weather conditions and digitizing error. In this MMU, most unvegetated area was classified as water/mudflat with two continuous patches of 63 ha and 7 ha, comprising a majority of the total.

In contrast to Salt Bayou MMU, vegetation loss in McNeil and Road MMU's accelerated from 1980 to 1987 (Figures 5, 6 and 7). The largest increase was in the mudflat category. In Road MMU, the largest mudflat area increase occurred from 1980 to 1983 and 1989 to 1991 (Figure 7). In addition, large continuous mudflats, which were apparent in 1983 changed little from 1983 to 1987 but expanded from 1987 to 1991 (Figure 6). The small scale and poor quality of the 1989 photographs for the McNeil MMU introduced a large error. Therefore, the 1987 and 1991 analyses were more accurate than that for 1989.

Field observations and measurements indicated that an increase in sparsely vegetated area from 1987 to 1989 and a decline in unvegetated area in Road MMU represented development of new openings (less than 50 $m^2$). This was due to moderate snow goose herbivory and cattle grazing in areas that had been continuously vegetated, and revegetation of open water and mudflat areas through: (1) expansion of remaining patches of vegetation (1989), (2) spread of vegetation from the perimeter of individual areas, (3) *Spartina alterniflora* plantings in a water/mudflat area, and (4) natural *S. alterniflora* recruitment. Conversely, sparsely vegetated area declined in 1991 with a concomitant increase in the water and mudflat categories. Sparse vegetation decline represented emergent vegetation regrowth in sparsely vegetated areas as a result of decreased salinities and improved water regime, removal of cattle and less LSG use of these areas. The increase in size of mudflats and open waters resulted from continuous LSG use along mudflat and open water area edges and higher water levels associated with increased precipitation and tide levels (Table 1).

### Lesser Snow Goose Population and Feeding Dynamics

LSG winter populations for all of Texas increased from 383,000 in the early-1950's to nearly 1,000,000 in the mid-1970's (Dzubin *et al.*, 1975; Haskins, 1992). LSG numbers decreased in the 1980's to approximately 700,000–800,000. Anecdotal field records and USFWS monthly aerial reconnaissance (available from 1972–1991 only) indicate that the number of LSG utilizing the refuge had been variable (Table 1). Refuge monthly activity reports and annual narratives described a "tremendous" increase in goose use in the mid-1970's compared to the early 1970's. Goose use was described as follows: "so many areas in the marsh are eaten out so sufficiently by snow geese that many areas, especially ponds, became large shallow water flats following concentrated continuous use from feeding and roosting habits of these waterfowl." Field observations indicate that in 1972–1973 from 50,000 to 80,000 geese heavily utilized *Distichlis spicata* flats and areas with *Spartina patens* interspersed with *D.*

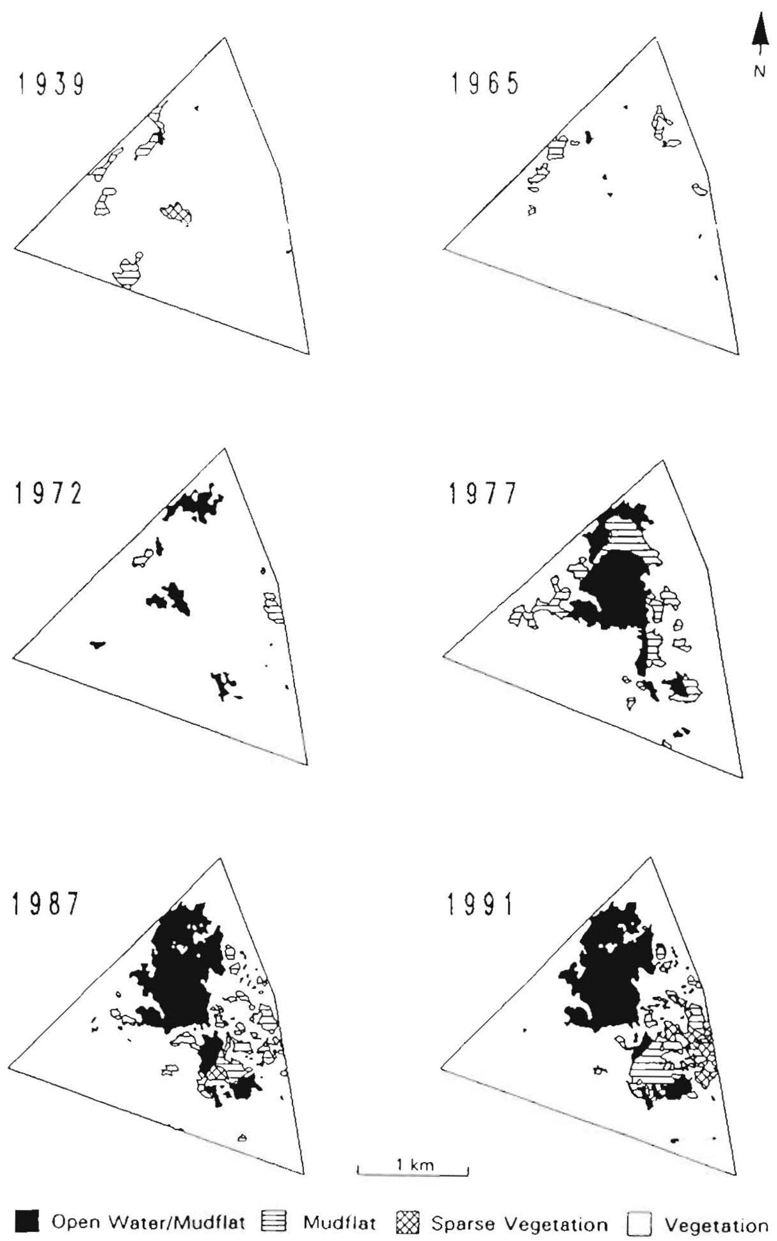


Figure 4. Spatial delineation of water/mudflat, mudflat, sparse vegetation and continuous emergent vegetation categories within a 386-ha section of Salt Bayou MMU in 1939, 1965, 1972, 1977, 1987, and 1991.

*spicata*. In 1973–1974 although 80,000 geese roosted in the marsh, feeding was reported as light compared to previous years.

The Texas Parks and Wildlife Department indicated that in 1974–1975 the largest concentration of snow geese in Texas occurred on SBNWR. Beginning in 1974–1975 and for the following two winters, goose numbers were estimated at around

Table 1. *Percent unvegetated area and area burned in Salt Bayou MMU, McNeil MMU, and Road MMU; peak LSG numbers determined by aerial surveys (unless noted); and extreme environmental conditions from 1972–1991.*

| | Salty Bayou MMU | | McNeil MMU | | Road MMU | | | |
|---|---|---|---|---|---|---|---|---|
| Year | Unvegetated (%) | Burned (%) | Unvegetated (%) | Burned (%) | Unvegetated (%) | Burned (%) | Peak LSG Numbers (× 1,000) | Extreme Environmental Conditions |
| 1972–1973[1] | 5 | — | — | — | 10 | — | — | High annual sea level |
| 1973–1974 | — | — | — | — | — | | | High annual sea level; spring/early summer and fall San Bernard River fresh water flooding; Tropical Storm Delia (Sep.) and above average rainfall (Oct.) |
| 1974–1975 | — | 5 | — | — | — | 25 | 100[2] | High annual sea level; above average annual rainfall |
| 1975–1976 | — | 0 | 6 | — | — | 10 | 102 | High annual sea level; below average annual rainfall |
| 1976–1977 | — | 21 | — | — | — | 0 | 100 | Low annual sea level |
| 1977–1978 | 24 | 0 | — | — | — | 0 | 65 | Below average annual rainfall; Hurricane Anita (Sep.) salt water flooded dry marsh with continued high water levels through Oct. |
| 1978–1979 | — | 0 | — | 22 | — | 24 | 42.2 | |
| 1979–1980 | — | 0 | — | 0 | — | 54 | 28 | High annual sea level; above average annual rainfall; extensive fresh water flooding; Tropical Storm Claudette (65–75 cm rainfall, July 24–26) |
| 1980–1981 | 23 | 0 | 5 | 19 | 15 | 32 | 62 | Below average annual rainfall; Hurricane Allen salt tide (30 ppt, 18–21 cm, Aug. 9) |
| 1981–1982 | — | — | — | 14 | — | 22 | 152 | |
| 1982–1983 | — | 0 | — | 20 | — | 25 | 85 | |
| 1983–1984 | 22 | 6 | 10 | 0 | 22 | 0 | 52.7 | High annual sea level; above average rainfall and additional rainfall associated with Hurricane Alicia (Aug. 17) |
| 1984–1985 | — | 0 | — | 5 | — | 0 | — | Above average rainfall |
| 1985–1986 | — | 0 | — | 0 | — | 0 | 19.1 | Above average rainfall |
| 1986–1987 | — | 0 | — | 0 | — | 5 | 19.7 | Hurricane Bonnie (Jun. 1986) salt tide |
| 1987–1988 | 26 | 0 | 13 | 19 | 30 | 3 | 21.3 | Below average rainfall |
| 1988–1989 | — | 0 | — | 14 | — | 0 | 18.6 | Low annual sea level; below average rainfall; Hurricane Gilbert high salt tide (50–70 cm deep in March, 23–26 ppt) |
| 1989–1990 | 23 | 0 | 12 | 0 | — | 0 | 5.8 | Below average spring rainfall; high rainfall and tides with Tropical Storm Allison (Jun. 26); salt tide over dry marsh with Hurricane Jerry (Oct. 18) |
| 1990–1991 | — | 0 | — | 0 | — | 0 | 28 | |
| 1991 | 26 | 0 | 18 | 0 | 19 | — | — | Above average rainfall; fresh water flooding |

[1]Year represents winter for snow goose numbers and prescribed burning
[2]Peak snow goose number for winter year-to-year

100,000 (Table 1). This occurred just prior to the 1975 aerial photography when extensive unvegetated areas, which have persisted, were noted in Salt Bayou MMU (Figure 4). In 1976, refuge records estimate 65% of the saline/brackish marsh was dominated by *D. spicata* with an estimated 1,400 ha of this vegetation type heavily utilized by LSG before December 31.

During the early 1980's, large areas dominated by *D. spicata* and *S. patens* were heavily used and large eatouts (completely denuded areas) were noted. LSG numbers declined in 1978–1980 but increased to 152,000 in December 1981 (a record for the refuge), and large numbers continued to utilize the marsh in the winter of 1981–1982. Monthly activity reports indicated partial recovery in some areas; however, recovery does not mean uprooted areas did not differ from areas unutilized by geese. Ground level photographs and recent field data indicate that vegetation was short-

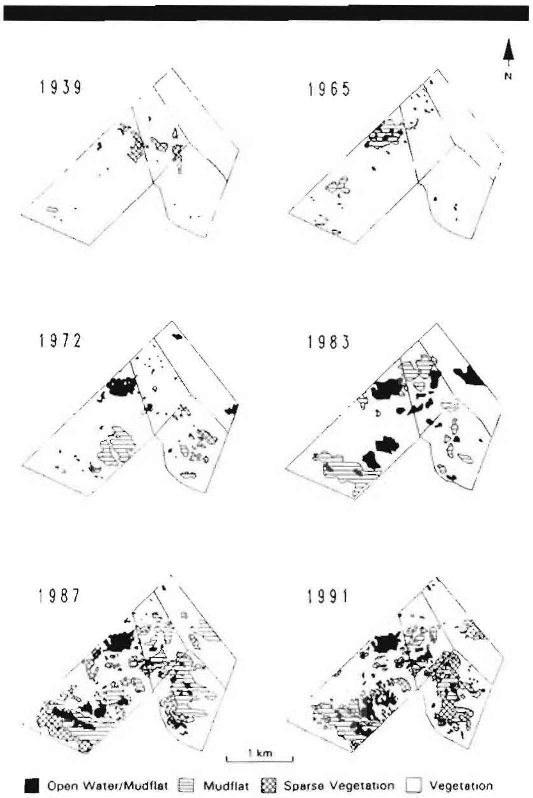


Figure 5. Spatial delineation of water/mudflat, mudflat, sparse vegetation and continuous emergent vegetation categories within a 418-ha section of McNeil MMU for 1939, 1961, 1980, 1983, 1987, and 1991. Analysis conducted on entire MMU. Subdivisions within MMU represent sites for field studies.

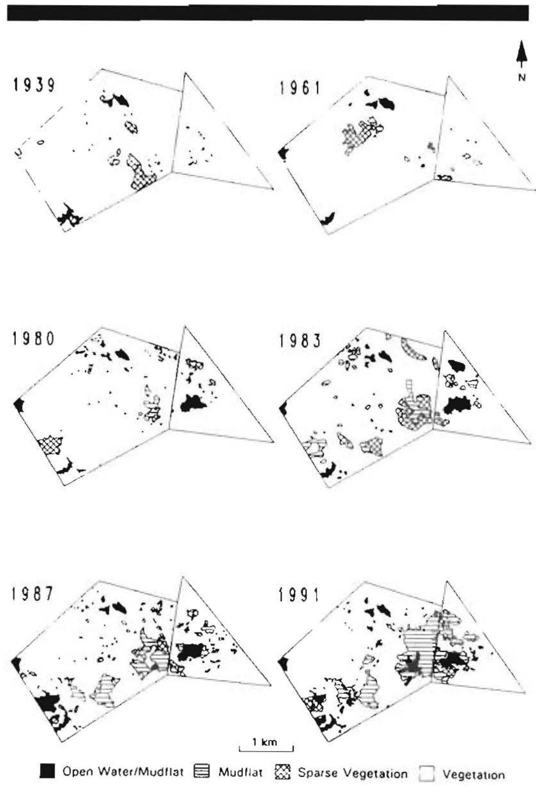


Figure 6. Spatial delineation of water/mudflat, mudflat, sparse vegetation and continuous emergent vegetation categories within a 811-ha section of Road/Riverbend MMU for 1939, 1965, 1972, 1983, 1987, and 1991.

er and sparser in heavily utilized areas (MILLER, 1993).

As vegetation loss accelerated, area available for goose feeding declined. While goose numbers began to decline in 1982–1983, numbers were well above those noted in the mid-to-late 1980's. Field observations and measurements indicated that while snow goose use was intense and widespread throughout the McNeil MMU 1987–1988, use was limited to the southwest section from 1988–1990. Although delayed in 1988, regrowth was extensive in 1989 and 1990 which accounts for the declines in unvegetated area noted in this unit (Figure 7). Recovery took place in areas heavily utilized by geese in 1987–1988 but not reutilized by geese in 1988–1989 or 1989–1990. Areas continuously utilized by geese (1987–1990), such as the largest continuous mudflats in the southwest section of McNeil and Road MMU (1987–1991), did not demonstrate the same mudflat revegetation (Figures 5, 6 and 7).

### Prescribed Burning and Cattle Grazing

Continuous areas of vegetation loss did not directly coincide with any single prescribed burn. However, in some cases, refuge records indicate geese utilized burned sites and areas nearby disproportionately more than unburned areas. Cattle have also been observed to preferentially utilize burned areas. Records indicate an area adjacent to the largest mudflat in Salt Bayou MMU was burned in November 1976. In addition, burns were conducted in the mid-1970's and early 1980's near or through areas where mudflats expanded in the 1980's (Table 1).

The sequence of events for one area of recent vegetation loss suggest burning alone did not cause vegetation loss. A prescribed burn of the southwest portion of McNeil MMU was conducted in

1978. It was noted to have revegetated (RON BISBEE, Project Leader Brazoria NWR, *personal communication*). In 1979, freshwater outflow was rerouted into this area. Aerial photography indicated the area was nearly continuously vegetated in 1980. In 1982–1983, geese heavily utilized the entire southwest portion of the McNeil MMU, and a large mudflat present in 1983, which has persisted, was noted to have failed to revegetate following goose use (RON BISBEE, Project Leader Brazoria NWR, *personal communication*).

Cattle management practices were altered throughout the period of vegetation change. Refuge reports prior to 1975 indicated only moderate use of 'cordgrass marsh' which appears to imply *Spartina patens* dominated marsh. At the same time, cattle heavily grazed uplands and adjacent *Spartina spartinae* dominated areas. In 1975, grazing was restricted to marsh and *S. spartinae* dominated areas to reduce marsh species, such as *Spartina patens,* to 50% or less of the composition and increase the abundance of *Distichlis spicata* and *Paspalum vaginatum*. Permanent monitoring plots established by the refuge in 1980 in Salt Bayou MMU and resampled in 1988 indicate a reduction in *S. patens* and an increase in *D. spicata* (*unpublished data*).

From 1982 to 1985, the heaviest cattle use occurred in areas near high ground (roads or *Spartina spartinae* dominated ridges) and in areas dominated by *Paspalum vaginatum* and *Distichlis spicata* (refuge utilization records). Similar use patterns were observed in 1988–1989 (*personal observation*). Estimation of *D. spicata* use in a portion of Salt Bayou MMU was at 85–90%. Refuge notes indicate heavy grazing of *D. spicata* in areas where *S. patens* and *D. spicata* were intermixed. Bare areas were described with "stools" of *S. patens* present. Areas dominated by *P. vaginatum* in McNeil and Road MMU had the heaviest cattle use, estimated at 80–95% of available aboveground growth. However, goose use was so extensive in all MMU's during this time that cattle use could not be assessed in all parts of each MMU.

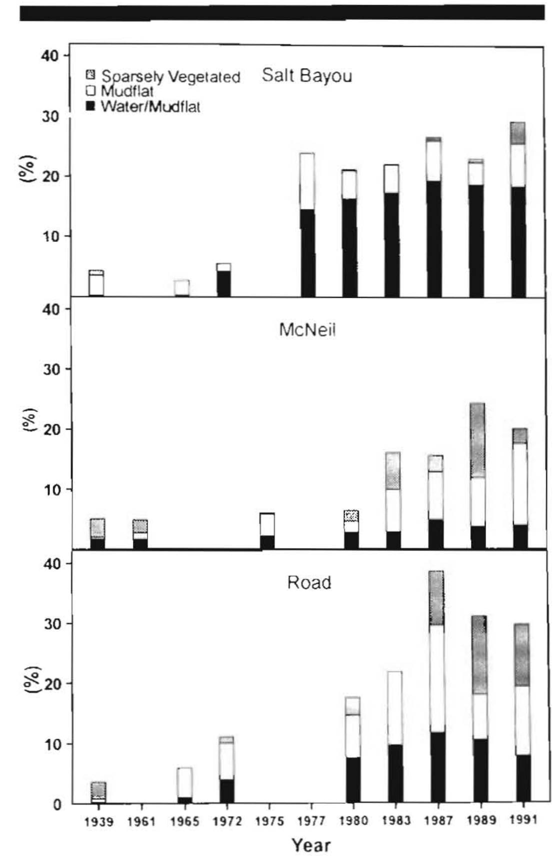


Figure 7. Percent of (a) Salt Bayou, (2) McNeil, and (c) Road MMUs (within area analyzed) delineated as water-mudflat, mudflat, and sparsely vegetated for selected years. Photography was not available for all MMUs for all years.

### Environmental Dynamics

Water levels and salinities within the SBNWR marshes were highly variable from 1939–1991 (Figures 2a, 2b and 3). Abnormally low water levels and high salinities were associated with droughts. Drought conditions reported for the spring of 1975 are evidenced by the completely dry marsh noted in aerial photography taken March 1975. Similar conditions were also noted throughout most of 1977 and 1978 and again from 1986 to 1988 (Figure 2). Soil water salinities measured in both vegetated areas and adjacent mudflats during the summer of 1988 ranged from 23–69 ppt with water levels well below the marsh surface for most of the summer months (MILLER, 1993). Rhizome production of all dominant marsh species was reduced. Drought conditions during the mid 1970's may have also resulted in comparably high salinities. More normal precipitation during the summer of 1989 and 1990 reduced salinities to 14–49 ppt with water depth ranging from −7 to 15 cm throughout the summer. Abnormally high water levels in the marshes were caused by both freshwater and saltwater flooding. High annual sea level occurred from 1972 to 1975 with additional peaks in 1979, 1983 and 1991 (Figure 3). Refuge records noted prolonged high water levels for the spring, early summer and fall of 1973 associated with flooding of the San Bernard River (spring and summer), Tropical Storm Delia (September) and above average rainfall (October). Additional high water levels, both fresh and salt, occurred in 1977, 1979, 1980, 1983, 1986, 1989 and 1991 (Table 1).

## DISCUSSION

Temporal and spatial patterns of landscape change indicate the significance of the interactions of physical disturbances, biotic processes and environmental constraints, (BAKKER and RUYTER, 1981) and aid in predicting future changes (SCANLAN and ARCHER, 1991). Accelerated conversion of vegetated marsh to mudflat and open water began on SBNWR in the late 1960's to early 1970's and has continued to the present. Changes were episodic and large unvegetated areas formed in short time spans. The largest open water and mudflat areas developed or expanded in the 1970's and in the early 1980's. However, not all mudflat and sparsely vegetated areas remained unvegetated.

Aerial photography was not taken frequently enough to conclusively link individual events, including LSG herbivory, environmental variation and management practices, to appearance of every mudflat. However, accelerated marsh change on SBNWR generally corresponds to periods of high LSG numbers on the Texas coast and on the refuge or to specific areas heavily utilized by geese. LSG populations have increased in recent decades on some of the breeding colonies where Texas snow geese originate (KERBES *et al.,* 1990). On these colonies, similar reductions in marsh vegetation have been linked to increased scale of denudation as a result of increased LSG numbers. Conversely, at least recently, periods or areas with reduced LSG numbers on SBNWR coincided with slower rates of vegetation loss and partial revegetation of some mudflats.

During the 1950s, Texas had a much smaller population of LSG (DZUBIN *et al.,* 1975; HASKINS, 1992) and LSG use of dry marshes (drought conditions) along the mid-Texas coast was limited. The increase in LSG in Texas during the 1960's and 1970's may relate to the agricultural practices along the migratory route as well as expansion of rice production in Texas with harvested acreage nearly doubling between 1941 and 1951, peaking in 1954 and declining in the 1970's and 1980's (KERBES *et al.,* 1990; ROBERTSON and SLACK, 1995). High numbers of LSG on the SBNWR during the mid-1970's and early 1980's may relate to the overall high population in Texas, the decrease in available rice fields and changes in refuge management practices. As vegetated marsh loss occurred, both on and off the refuge, smaller vegetated marsh areas were available for LSG use.

Refuge records indicate that sites where persistent mudflat and water areas recently replaced emergent vegetation were intensely and frequently used for feeding and roosting by large numbers of geese (30,000–100,000) during and after the changes first occurred. Recent observation noted that the most frequently utilized roost sites (1988–1991) were the largest recently developed mudflats (refuge records, *personal observation,* JENNINGS, 1990; ROBERTSON, 1991). In 1989 and 1990, geese returned to the last place they fed the preceding year. LYNCH *et al.* (1947) reported that geese sometimes return to uproot vegetation regrowth before reestablishment is complete. As a result of frequent intense use, propagule supplies are reduced and revegetation delayed.

Aerial photographs and refuge eatout surveys indicate the largest water/mudflat in Salt Bayou MMU did not revegetate following LSG use in the mid 1970's. Direct observation verified that at least one of the larger mudflats on SBNWR failed to revegetate following heavy snow goose use in the early 1980's (RON BISBEE, project leader Brazoria NWR, *personal communication*). Also, several areas of heavy goose use in 1988 and 1989 have failed to revegetate while adjacent unutilized vegetation remains intact (MILLER, 1993). However, other LSG denuded areas throughout the refuge partially revegetated after LSG use and complete recolonization occurred only with reduced frequency and intensity of LSG use.

While not singularly responsible, prescribed burning and cattle grazing may have contributed to loss of marsh vegetation or revegetation failure of denuded areas. Cattle grazing may contribute to reduced resistance and resilience in areas of high concentration. Cattle were concentrated from 1982 to 1985 near two of the recently produced or expanding mudflats. In addition, high density of hoof prints and trails on some recently created mudflats was documented in refuge photographs. Reduced sedimentation, reduced plant regeneration, decreased canopy height and increased salinity have been associated with heavy cattle grazing and trampling (CHABRECK, 1968; BAKKER, 1985; JENSEN, 1985; LAVADO and TABOADA, 1987; ANDRESEN *et al.*, 1990). However, light cattle grazing has had little effect.

Various investigators have noted preferential use of burned marsh by geese and cattle (MCATEE, 1910; SINGLETON, 1951; CHABRECK, 1982; SMITH and KADLEC, 1985; ALISAUSKAS, 1988). Refuge records indicate some of the areas burned in the 1970's and 1980's later developed into mudflats. These areas were also utilized by snow geese and cattle. However, the majority of the areas burned during the 1970's and 1980's did not lose emergent marsh vegetation.

Sedimentation rates (or inversely erosion rates), water salinity and water levels represent constraining environmental factors to which the vegetation responds. The oldest and largest continuous mudflat and open water areas generally are found in low topographic areas near tidal creeks. Across the marsh, these areas usually have the highest salinities and are most frequently affected by water level and salinity fluctuation. Most recently (1980-present), these areas were dominated by *Distichlis spicata* or a mosaic of *Spartina patens, Distichlis spicata, Paspalum vaginatum* and *Scirpus robustus*. Within the marsh, as distance from tidal influence increases, resilience of the vegetation increases.

Global climatic variation such as La Nina and El Nino events has been linked in other areas to local environmental variation such as that noted along the mid-Texas coast (KERR, 1988; TRENBERTH *et al.*, 1988; CHILDERS *et al.*, 1990). La Nina events were reported in 1975 and 1988 and early 1989, which correspond to the most recent extended drought periods in the area. Replacement of emergent vegetation by mudflats on the refuge in the 1970's corresponds to a period of drought preceded by several years of high precipitation and annual tides. However, *D. spicata, S. patens, S. americanus* and *S. virginica,* while reduced by drought, are not eliminated (MILLER, 1993). Mudflat increase during the 1988 and 1989 drought was documented in areas of heavy LSG-use only (MILLER, 1993). Vegetation loss did not occur during other periods of extended drought including the 1950's.

Increased San Bernard River outflow and above average local precipitation and tide levels in fall, spring and early summer may be linked to El Nino events (KERR, 1988; TRENBERTH *et al.*, 1988; CHILDERS *et al.*, 1990). The strongest El Nino of the century was reported in 1982–1983 with a strong El Nino in 1972–1973 and a mild El Nino in 1976–1977 (KERR, 1988; CHILDERS *et al.*, 1990). In 1973 and 1983, above average water levels in refuge marshes were reported in all seasons in response to all factors mentioned above. Accelerated vegetation loss also corresponded to peaks in precipitation and annual tide levels noted in the early to mid-1970's and 1983 but not to the 1979 peak. After extended high tides in 1990 and 1991 new unvegetated areas were noted only in areas of heavy LSG-use.

Vegetation changes associated with tropical storms and hurricanes are mostly temporary (CHABRECK and PALMISANO, 1973). Hurricane Carla, the largest storm to influence the Texas coast in the last 50 years, did not form large mudflats or open water areas on SBNWR. However, LYNCH *et al.* (1947) and MEEDER and PERRY (1990) reported that ponds formed when uprooted vegetation and marsh sediment unanchored by vegetation was washed out by storm tides. On SBNWR seasonally high tides and storm tides have transported sediment and organic debris into and out of areas heavily used by geese (*personal observation*).

Although others factors can accelerate rate of marsh loss such as submergence and salt water intrusion (TURNER, 1990), these factors were not evaluated. However, geologic faults identified on the refuge do not correspond with any areas of loss. Land subsidence and activation of surface faulting is not presently considered a major problem in the study area (BROWN *et al.*, 1974). Land-surface subsidence was reported to be 6 to 30 cm during the past 3 or 4 decades (WHITE *et al.*, 1988). Road and drainage ditch development which has possibly altered freshwater availability within the basin's watershed has continued throughout the 52 years covered on the aerial photography, and the Intracoastal Waterway is dredged at intervals of 4 to 10 years.

Rate of revegetation following LSG herbivory is influenced by post herbivory hydroperiod and water depth, salinity, storm tide timing and severity, and water turnover (LYNCH *et al.*, 1947; MEEDER and PERRY, 1990; MILLER, 1993). Loss of emergent marsh to open water is caused by prolonged flooding or high salinities, which prevents seed germination and results in death of rhizome fragments and discarded culm nodes. Seedlings and new growth that develop following herbivory are killed by floods, droughts or salt water. Even when environmental conditions do not totally preclude regrowth, vegetation with decreased stature and root and rhizome development as a result of frequent, intense LSG herbivory may have reduced resistance to extended inundation or drought. In addition, LSG may continue to use marsh sites that have converted to mudflats and open water. Reduced marsh vegetation height, cover, and net production has been reported in response to LSG herbivory on SBNWR and in coastal marsh communities of similar composition (SMITH and ODUM, 1981; MILLER, 1993).

Vegetation contributes to marsh aggradation by trapping sediment, accumulating organic matter and forming root material belowground (TURNER, 1990). Reduced vegetation acts as a positive feedback and subjects unvegetated mudflats to erosion by waves and currents, increased salinity and algal mat formation (IACOBELLI and JEFFERIES, 1991). NYMAN *et al.* (1994) recognized erosion as a mechanism of wetland loss in Louisiana and speculated that small ponds created by herbivores such as LSG and muskrats might serve as starting points for erosion of interior marsh surfaces. Erosion is also more likely to occur where rhizomes and root systems are not well developed. Destabilization of soil associated with loss of sedge rhizomes as a result of LSG and muskrat herbivory has been reported (MEEDER and PERRY, 1990; IACOBELLI and JEFFERIES, 1991). In Salt Bayou MMU, the large mudflat that developed in the 1970's has deepened into an open water area as the roots and rhizomes deteriorated or eroded. Fewer mudflats or portions of mudflats have become open water areas in McNeil and Road. The smaller extent of open water in these two MMU's may be related to the more recent development of these mudflats and thus reduced exposure to erosion.

## SUMMARY AND CONCLUSIONS

Field investigation on plant communities and individual species at the SBNWR suggests that the effects of prolonged extremes in salinities and water level interacting with increased intensity, frequency and scale of LSG feeding and roosting could have resulted in changes noted at the landscape level (MILLER, 1993). Long-term records indicate that maximum salinities, water levels and snow goose use coincided with the location and timing of the landscape changes. Both *S. americanus* and *D. spicata* community types are more resistant and resilient to observed extreme environmental fluctuations than to the combined effects of intense LSG use and extreme environmental conditions. A combination of disturbance agents appears more likely to result in rapid, persistent mudflat formation, while an intense, transient, or moderate, extended occurrence of a single disturbance agent is more likely to result in a short-term or slow, cumulative change in these communities.

Mudflat persistence and/or further degradation once initiated appears to be associated with tidal influence which affects salinity, water depth, hydroperiod, erosion, sedimentation and potential colonizers. Frequent extreme environmental fluctuations reduce the frequency and intensity of goose use necessary for permanent mudflat formation and reduce the potential for colonization by species other than those previously on site. Other agents such as concentration of cattle may slow recolonization of mudflats. Additional disturbances such as long-term high water associated with subsidence and seasonal and annual sea level variation may increase the likelihood of mudflat formation. Frequent rapid fluctuation in water level is also more likely to result in erosion. Elevation loss may represent a threshold where persistent mudflat replaces emergent marsh. However, rapid revegetation may occur when reduced salinities and moist soil conditions occur.

A shifting mosaic pattern appears to be more frequently associated with LSG herbivory in areas of reduced tidal influence and increased elevation. Diminished rapid water level fluctuations reduce the potential for elevation loss which increase the possibility for recolonization. In addition, consistently lower salinities normally found further from tidal influence permit colonization of open patches by a greater number of plant species. Under these environmental conditions, snow goose herbivory may result in temporary increases in structural diversity and species richness and permanent mudflat formation may be avoided.

Observation of reduced resistance and resilience indicates added disturbance or stress factors should be avoided if increases in mudflat size or permanent mudflat formation are not desired. Management practices that attract geese to other marsh areas less susceptible to persistent change, removal of cattle from these areas, and avoidance of burning along the edge of mudflats may reduce the rate of marsh loss.

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## LITERATURE CITED

ALISAUSKAS, R.T., 1988. Winter diets and nutrition of midcontinental lesser snow geese. *Journal of Wildlife Management,* 52, 403–414.

ANDRESEN, H.; BAKKER, J.P.; BRONGERS, M.; HEYDEMANN, B., and IRMLER, U., 1990. Long-term changes of salt marsh communities by cattle grazing. *Vegetatio,* 89, 137–148.

ARCHER, S. and SMEINS, F.E., 1991. Ecosystem-level processes. *In:* HEITSCHMIDT, R.K. and STUTH, J.W. (eds.), *Grazing Management: An Ecological Perspective.* Portland, Oregon: Timber Press, pp. 109–139.

BAKKER, J.P., 1985. The impact of grazing on plant communities, plant populations and soil conditions on salt marshes. *Vegetatio,* 62, 391–398.

BAKKER, J.P. and RUYTER, J.C., 1981. Effects of five years of grazing on salt marsh vegetation. *Vegetatio,* 44, 81–100.

BROWN, L.F. JR.; MORTON, R.A.; MCGOWEN, J.H.; KREITLER, C.W., and FISHER, W.L., 1974. *Natural Hazards of the Texas Coastal Zone.* Austin, Texas: The University of Texas at Austin, Bureau of Economic Geology Special Publication.

CHABRECK, R.H., 1968. The relations of cattle and cattle grazing to marsh wildlife and plants in Louisiana. *Proceedings of the Annual Conference of the Southeast Association Game and Fish Commissioners,* 22, 55–68.

CHABRECK, R.H., 1982. Effect of burn date on regrowth rate of *Scirpus olneyi* and *Spartina patens. Proceedings of the Annual Conference of the Southeast Association Fish and Wildlife Agencies,* 35, 201–210.

CHABRECK, R.H., 1988. *Coastal Marshes.* Minneapolis, Minnesota: University of Minnesota Press, 138p.

CHABRECK, R.H. and PALMISANO, A.W., 1973. The effects of Hurricane Camille on the marshes of the Mississippi river delta. *Ecology,* 54, 1118–1125.

CHILDERS, D.L.; DAY, J.W., and MULLER, R.L., 1990. Relating climatological forcing the coastal water levels in Louisiana estuaries and the potential importance of El Nino-Southern Oscillation events. *Climate Research,* 1, 31–42.

CHOU, R.C.; VARDY, C. and JEFFERIES, R.L., 1992. Establishment from leaves and other plant fragments produced by the foraging activities of geese. *Functional Ecology,* 6, 297–301.

DAHL, T.E., 1990. *Wetland Losses in the United States 1780s to 1980s.* Washington, D.C.: U.S. Department of the Interior, Fish and Wildlife Service.

DZUBIN, A.; BOYD, H., and STEPHEN, W.J.D., 1975. Blue and snow goose distribution in the Mississippi and central flyways, 1951–71. *Canada Wildlife Service Progress Note,* No. 54.

FULLER, D.A.; SASSER, C.E.; JOHNSON, W.B., and GOSSELINK, J.G., 1985. The effects of herbivory on vegetation on islands in Atchafalaya Bay, Louisiana. *Wetlands,* 4, 105–114.

HASKINS, J., 1992. *Analysis of Selected Mid-winter Waterfowl Survey Data 1955-1991, Region 2 (Central Flyway Portion),* U.S. Fish and Wildlife Service, Albuquerque, New Mexico.

HATCH, S.L.; KANCHEEPURAM, G.N., and BROWN, L.E., 1990. *Checklist of the Vascular Plants of Texas.* College Station, Texas: The Texas Agricultural Experiment Station, Texas A&M University System MP-1655, 158p.

IACOBELLI, A. and JEFFERIES, R.L., 1991. Inverse salinity gradients in coastal marshes and the death of stands of *Salix*: The effects of grubbing by geese. *Journal of Ecology,* 79, 61–73.

JEFFERIES, R.L.; JENSEN, A., and ABRAHAM, K.F., 1979. Vegetational development and the effect of geese on vegetation at La Perouse Bay, Manitoba. *Canadian Journal of Botany,* 57, 1439–1450.

JENNINGS, A.F., 1990. Roost Dynamics and Site Fidelity of Snow Geese Wintering in Southeast Texas. Master's Thesis, College Station, Texas: Texas A&M University, 58p.

JENSEN, A., 1985. The effect of cattle and sheep grazing on salt marsh vegetation at Skallingen, Denmark. *Vegetatio,* 60, 37–48.

KERBES, R.H.; KOTANEN, P.M., and JEFFERIES, R.L., 1990. Destruction of wetland habitats by lesser snow geese: A keystone species on the west coast of Hudson bay. *Journal of Applied Ecology,* 27, 242–258.

KERR, R.A., 1988. La Nina's big chill replaces El Nino. *Science,* 241, 1037–1038.

LAVADO, R.S. and TABOADA, M.A., 1987. Soil salinization as an effect of grazing in a native grassland soil in the flooding pampa of Argentina. *Soil Use and Management,* 3, 143–148.

LUDEKE, A.K.; MAGGIO, R.C., and REID, L.M., 1990. An analysis anthropogenic deforestation using logistic regression and GIS. *Journal of Environmental Management,* 31, 247–259.

LYNCH, J.J.; O'NEIL, T., and LAY, D.W., 1947. Management significance of damage by geese and muskrats to Gulf Coast marshes. *Journal of Wildlife Management,* 11, 50–76.

MCATEE, L., 1910. Notes on *Chen caerulescens, C. rossi,* and other waterfowl in Louisiana. *Auk,* 27, 337–339.

MEEDER, J.F. and PERRY, E., 1990. Ecosystem impacts and recovery rates of overgrazing by snow geese and muskrat in brackish marshes in southwest Louisiana. *Bulletin of the Ecology Society of America 71 (2 supplement).*

MENDELSSOHN, I.A. and MCKEE, K.L., 1988. Response of a freshwater marsh plant community to increased salinity and increased water level. *Aquatic Botany*, 35, 301–316.

MILLER, D.M., 1993. Effects of lesser snow goose herbivory on Mid-Texas coastal marsh vegetation dynamics. Ph.D. dissertation, College Station, Texas: Texas A&M University, 206p.

NATIONAL COOPERATIVE SOIL SURVEY, 1981. *Soil Survey of Brazoria County, Texas.* U.S. Department of Agriculture, Soil Conservation Service, in cooperation with Brazoria County Commissioners Court and Texas Agricultural Experimental Station.

NYMAN, J.A.; CARLOSS, R.D.; DELAUNE, R.D., and PATRICK, W.H., JR., 1994. Erosion rather than plant dieback as the mechanism of marsh loss in an estuarine marsh. *Earth Surface Processes and Landforms*, 19, 69–84.

ROBERTSON, D.G., 1991. *Movements and Habitat Use of Lesser Snow Geese Wintering on the Upper Texas Coast.* Master's thesis, College Station, Texas: Texas A&M University.

ROBERTSON, D.G. and R.D. SLACK, 1995. Landscape change and its effects on the wintering range of a lesser snow goose population: A review. *Biological Conservation*, 71, 179–185.

SALINAS, L.M.; DELAUNE, R.D., and PATRICK, W.H., JR., 1986. Changes occurring along a rapidly submerging coastal area: Louisiana, USA. *Journal of Coastal Research*, 2, 269–284.

SCANLAN, J.C. and ARCHER, S., 1991. Simulated dynamics of succession in a North American subtropical *Prosopis* savanna. *Journal of Vegetation Science*, 2, 625–634.

SINGLETON, J.R., 1951. Production and utilization of waterfowl food plants on the East Texas Gulf coast. *Journal of Wildlife Management*, 15, 46–56.

SMITH, L.M. and KADLEC, J.A., 1985. Fire and herbivory in a great salt lake marsh. *Ecology*, 66, 259–265.

SMITH, T.J., III and ODUM, W.E., 1981. The effects of grazing by snow geese on coastal salt marshes. *Ecology*, 62, 98–106.

THORNTHWAITE, C.W., 1948. An approach toward a rational classification of climate. *Geographical Review*, 38, 185–311.

TINER, R.W., 1984. *Wetlands of the United States—Current Status and Recent Trends.* Washington, D.C.: U.S. Department of Interior, Fish and Wildlife Service.

TRENBERTH, P.A.; BRANSTATOR, K.E., and ARKIN, G.W., 1988. Origins of the 1988 North American drought. *Science*, 242, 1640–1645.

TURNER, R.E., 1990. Landscape development and coastal wetland losses in the northern Gulf of Mexico. *American Zoological*, 30, 89–105.

TURNER, R.E. and CAHOON, D.R., (eds.), 1987. *Causes of wetland loss in the coastal central Gulf of Mexico.* Final report submitted to the Minerals Management Service, New Orleans, Contract No. 14-12-001-30252, OCS Study/MMS 87-0119.

WHITE, W.A.; CALNAN, T.R.; MORTON, R.A.; KIMBLE, R.S.; LITTLETON, T.G.; MCGOWEN, J.H., and NANCE, H.S., 1988. *Submerged Lands of Texas, Bay City-Freeport Area: Sediments, Geochemistry, Benthic Macroinvertebrates, and Associated Wetland.* Austin, Texas: The University of Texas at Austin, Bureau of Economic Geology, 140p.

WHITE, W.A.; TREMBLAY, T.A.; WERMOND, E.G., and HANDLEY, L.R., 1993. Status and trends of wetlands and aquatic habitats. *In:* JENSEN, R.W.; KIESLNG, R.W., and SHIPLEY, F.S. (eds.), *Galveston Bay National Estuary Program.* Publication NEP.23. pp. 201–205.