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The effect of tidal exclusion on salt marsh vegetation in Baja California, México

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Abstract

Changes in salt marsh vegetation were analyzed over a two-year period (November 1984-November 1986) following the construction of a dike in the southwest corner of Punta Banda Estuary, Baja California, México. Changes included: increased interstitial soil salinity, reduced soil moisture, increased mortality of *Spartina foliosa* and decreased middle marsh species diversity due to the elimination of annual and short-lived species. The sea-side edge of the middle marsh shifted its boundary to a lower elevation. By the end of 1986, dominant species were *Salicornia virginica*, *Batis maritima* and *Frankenia grandifolia*. By October 1988, only a few patches of *S. foliosa* persisted at the water edge, and it appeared that the community was not yet stable. The potential future of the estuary is evaluated.

Introduction

Baja California is well known for the beauty and wilderness of its natural resources. For many years, the relative isolation of the peninsula allowed these resources to remain untouched; however, this situation has been rapidly changing in the last two decades.

The most significant event to affect the natural resources of Baja California was the December 1973 completion of the transpeninsular highway. The 1600 km long highway linked the north and south extremes of the peninsula, as well as southern California with Baja California. It has been estimated that since 1973, tourism has increased 500%, sportfishing 400%, hunting 100%, whale watching 100% and commercial trucking 600%. This increase in human use of Baja California has impacted waterfowl resources in some areas (Kramer and Migoya 1989). In addition, Baja's inhabitants increased by 35.3% between 1970 and 1980 (INEGI 1987).

Estuaries along the Pacific Coast of Baja California were nearly pristine until 1984, when an international oil company introduced structural modifications in Punta Banda Estuary (Fig. 1). As part of the project, a dike was built to isolate the industrial area from the rest of the estuary, thus excluding a 0.21 km^2 area from the tidal regime. This project offered us the opportunity to study marsh vegetation responses to tidal exclusion. The purpose of this research was to see if marsh vegetation in Punta Banda Estuary would change in the same manner as in Tijuana Estuary, California, which was closed to tidal flows a few months earlier (Zedler 1982; Zedler and Nordby 1986). Observed changes in Tijuana Estuary included mortality of *Spartina foliosa* and elimination of annual and short-lived species. In addition, we hoped to develop recommendations that would help manage development within estuaries.

Fig. 1. Aerial view of Punta Banda Estuary before 1983. The L-shape of the estuary is clearly seen.

Methods

Study area

The Punta Banda Estuary (31°40′-31°48′N; 116°34′-116°40′W) is located 123 km south of the México-USA border and 12 km south of the city of Ensenada. It covers an area of 21 km^2, of which marshes represent 3.3 km^2 (Fig. 2). A detailed description of the physical and biological features of the estuary has been given by Ibarra-Obando and Escofet (1987).

The Mediterranean climate of the area, characterized by warm, dry summers and cool, moist win-

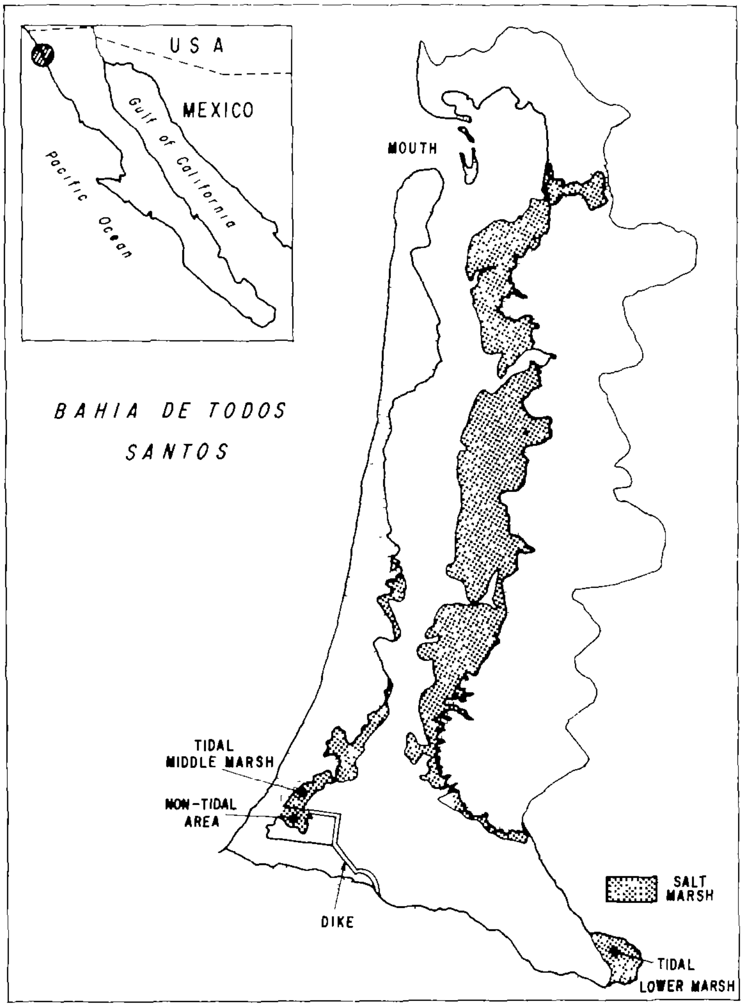

Fig. 2. Updated map of the estuary. Geographic location, industrial project, and salt marsh areas are indicated. Study areas are indicated with an '×'. Notice the change in shape of the sand bar tip with respect to Fig. 1.

ters, determines the hypersaline nature of tidal marshes in Northern Baja California (Zedler 1982). Rainfall is highly variable and unpredictable. For a ten-year period between 1978 and 1988, only 1978, 1980 and 1983 could be considered rainy years, having annual precipitation averages around 500 mm. Remaining years in this period had annual averages close to 230 mm (Secretaría de Agricultura y Recursos Hidráulicos, personal communication). During summer and fall, evaporation usually exceeds precipitation. Under these circumstances, tides are the principal water source for intertidal wetland plants (Zedler 1982).

Punta Banda Estuary is important for fish reproduction and as a feeding and resting place for migratory birds (Ibarra-Obando and Escofet 1987). Due to wetlands destruction along the California coastline, Northern Baja California marshes have become reservoirs for rare and endangered species such as the light-footed clapper rail (*Rallus longirostris levipes*), the Belding's Savannah sparrow (*Passerculus sandwichensis beldingi*), California least tern (*Sterna albifrons browni*), and the saltmarsh bird's beak (*Cordylanthus maritimus* ssp. *maritimus*).

The installation of an assembling plant for oil-drilling platforms introduced structural modifications in the estuary. In May 1984 the construction

Fig. 3. 1989 aerial view of the dike in the southwest corner of the estuary. The section of marsh studied inside the dike is clearly seen. Reclamation areas inside the dike, as well as sand dunes leveling and marsh destruction along the sand bar are also evident.

Fig. 4. 1989 aerial view of the tidal lower marsh at the head of the estuary. *Spartina foliosa* in this area was compared with the lower marsh inside the dike.

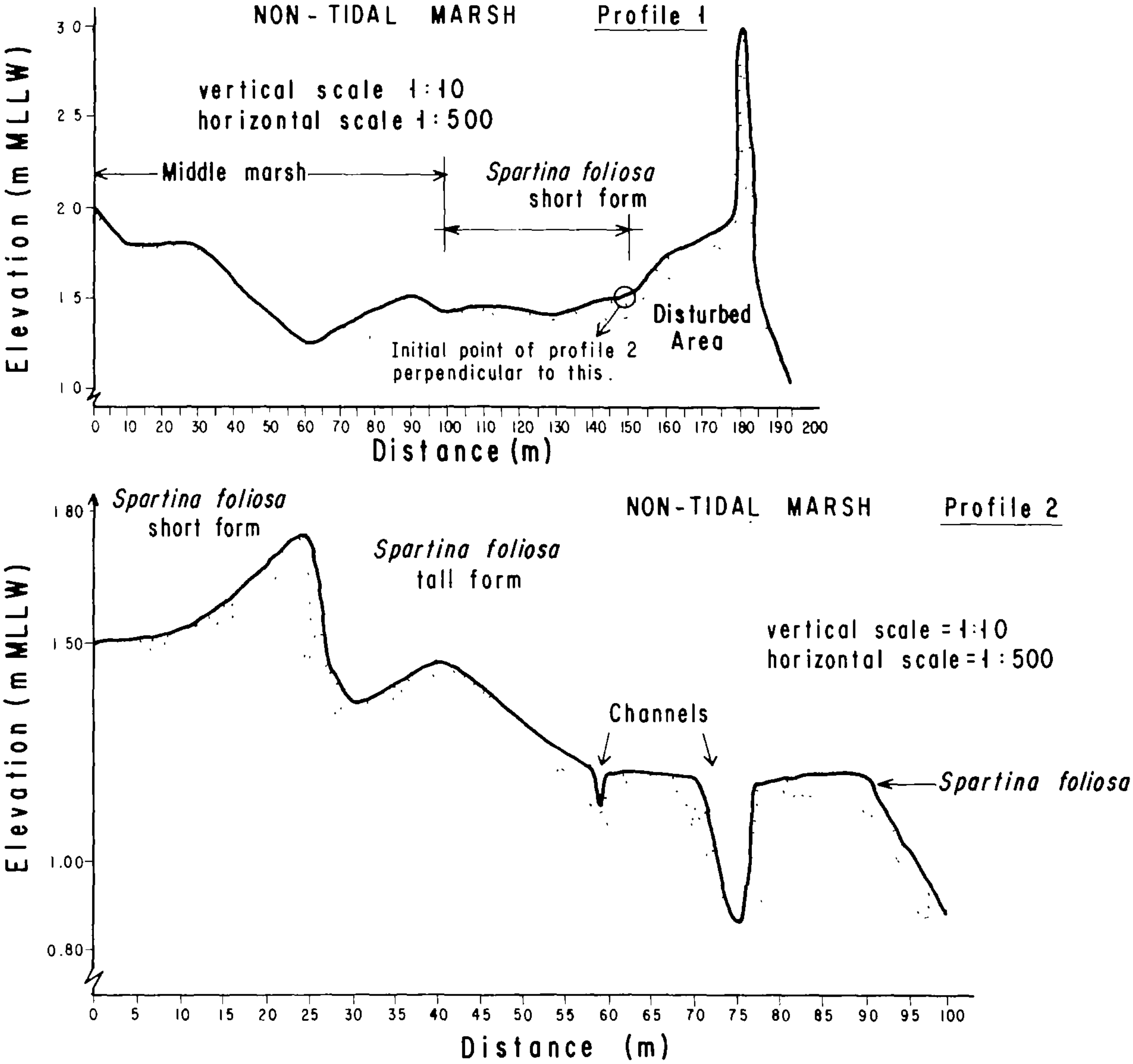

Fig. 5. Topographic profiles of the non-tidal marsh. Top profile represents the middle marsh and the short *Spartina foliosa* form zone. Bottom profile represents short and tall *S. foliosa* zones. Both profiles represent post-disturbance conditions. (MLLW = mean low low water).

of a dike in the southwest corner was initiated. Two months later, when the dike was finished, an area of 0.21 km^2 had been isolated from the tidal regime. The water body within the dike was dredged to a depth of 9 m to allow for construction of the assembling pit. The dredged material was used to fill the marsh and create the industrial patio (Fig. 3). Four months after the dike was completed but before all the filling was done, we began monitoring vegetation in the only portion of marsh that was left inside the dike (Fig. 3). Marsh species diversity in this area was compared with two non-disturbed areas outside the dike, over a two-year period.

Field work

Salt marsh vegetation was divided into two categories: lower and middle marsh. The lower marsh

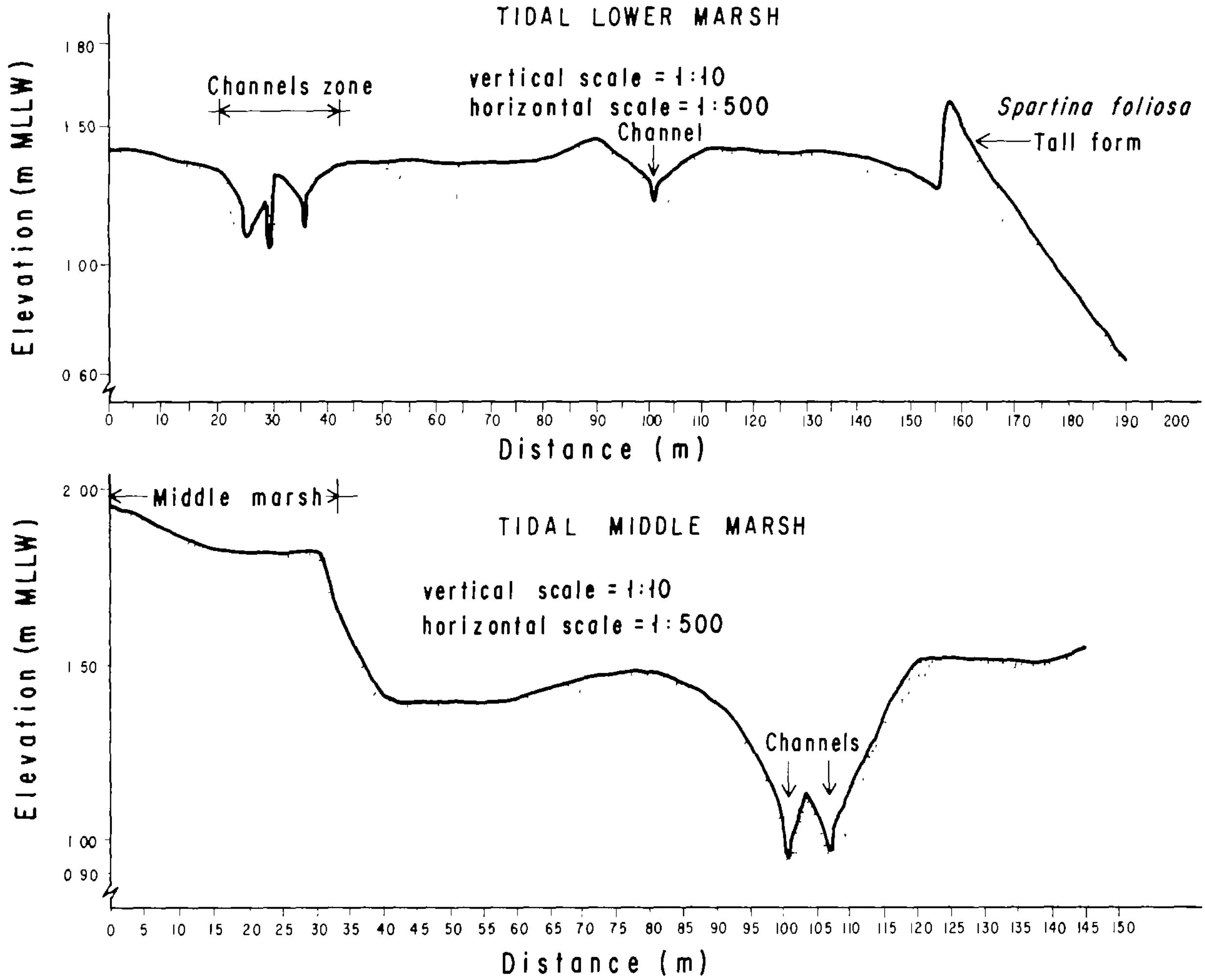

Fig. 6. Topographic profiles of the two tidal areas. Top, lower marsh. Bottom, middle marsh.

was dominated by *Spartina foliosa* with its two growth forms: tall and short. The tall form zone was characterized by pure stands of *S. foliosa*. Average stem height at the end of the growing season (September) varied between 71 and 130 cm. The short form zone was comprised of *S. foliosa* mixed with *Batis maritima* and *Salicornia virginica*. Average stem height at the end of September ranged from 33 to 76 cm. The middle marsh is characterized by a mixture of species, including several perennials (*B. maritima, S. virginica, Frankenia grandifolia, Jaumea carnosa, Monanthocloe littoralis, Distichlis spicata, Limonium californicum*), a short-lived species (*Suaeda esteroa*) and annuals (*Salicornia bigelovii, Triglochin* sp., *Cuscuta salina*).

Lower marsh vegetation inside the dike (non-tidal area) was compared with vegetation at the southeastern end of the estuary (tidal area; Fig. 4). These two areas were considered comparable because they were located at the head of the estuary and were subjected to the same circulation pattern. Middle marsh vegetation was not extensive at this tidal site due to low intertidal elevation. A second tidal area was located 0.5 km north of the non-tidal area in the sand bar, where middle marsh species were dominant (Fig. 2).

Topographic profiles of the three sampling stations are presented in figures 5 and 6 (non-tidal area profiles represent post-disturbance conditions). The non-tidal lower marsh transect was 90 m long,

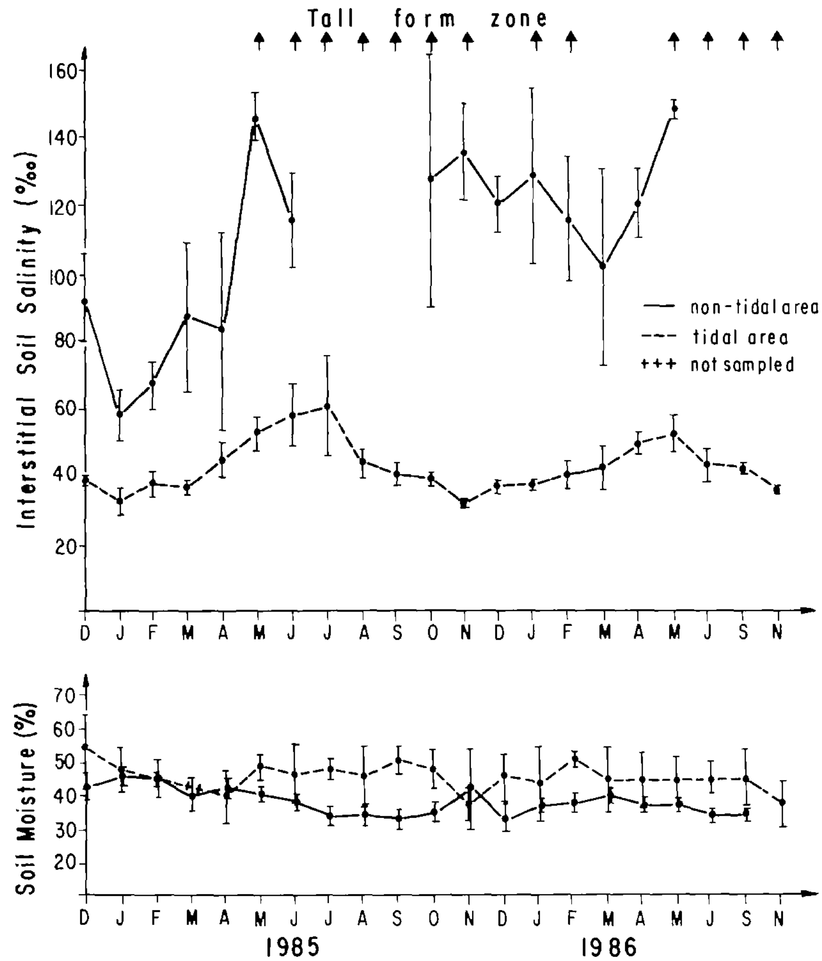

Fig. 7. Sediment physical characteristics of the tall *S. foliosa* zone. Top, interstitial soil water salinity measured in parts per thousand (‰). Arrows indicate values exceeding the scale of the refractometer at the non-tidal area. Bottom, percentage soil moisture for tidal and non-tidal areas. Note that soil moisture values differ little between tidal and non-tidal areas. Bars represent ±1 SE.

varying between 40 and 80 m in width, with an elevation range of 1.50 to 0.87 m mean low low water (MLLW; Fig. 5). The tidal lower marsh transect was 190 m long, 20 m wide, and 1.46 to 0.68 m MLLW (Fig. 6). The non-tidal middle marsh transect was 100 m long, 80 m wide, and 2.00 to 1.25 m MLLW (Fig. 5). The tidal middle marsh transect was 33 m long and 50 m wide, with an elevation range of 1.95 to 1.64 m MLLW (Fig. 6).

In the non-tidal area and the tidal area at the head of the estuary, sampling was monthly from November 1984 to May 1986 and bimonthly from June to November 1986. The tidal middle marsh was first sampled in May 1985. In this area sampling was monthly until May 1986 and bimonthly from June to November 1986.

Lower marsh vegetation. The lower marsh was divided into a tall *S. foliosa* zone and a short form zone. In both the tidal and non-tidal areas, ten 0.25 m^2 circular quadrats were randomly placed each month per zone. Quadrats were located having as reference two imaginary axes, the X-axis being represented by the width of the sampled zone and the Y-axis by its length. Quadrat coordinates were randomly chosen each time.

In each quadrat we measured interstitial soil water salinity, by refractometer. Soil samples were collected with a plastic core (1.5 cm diameter) at 2-3

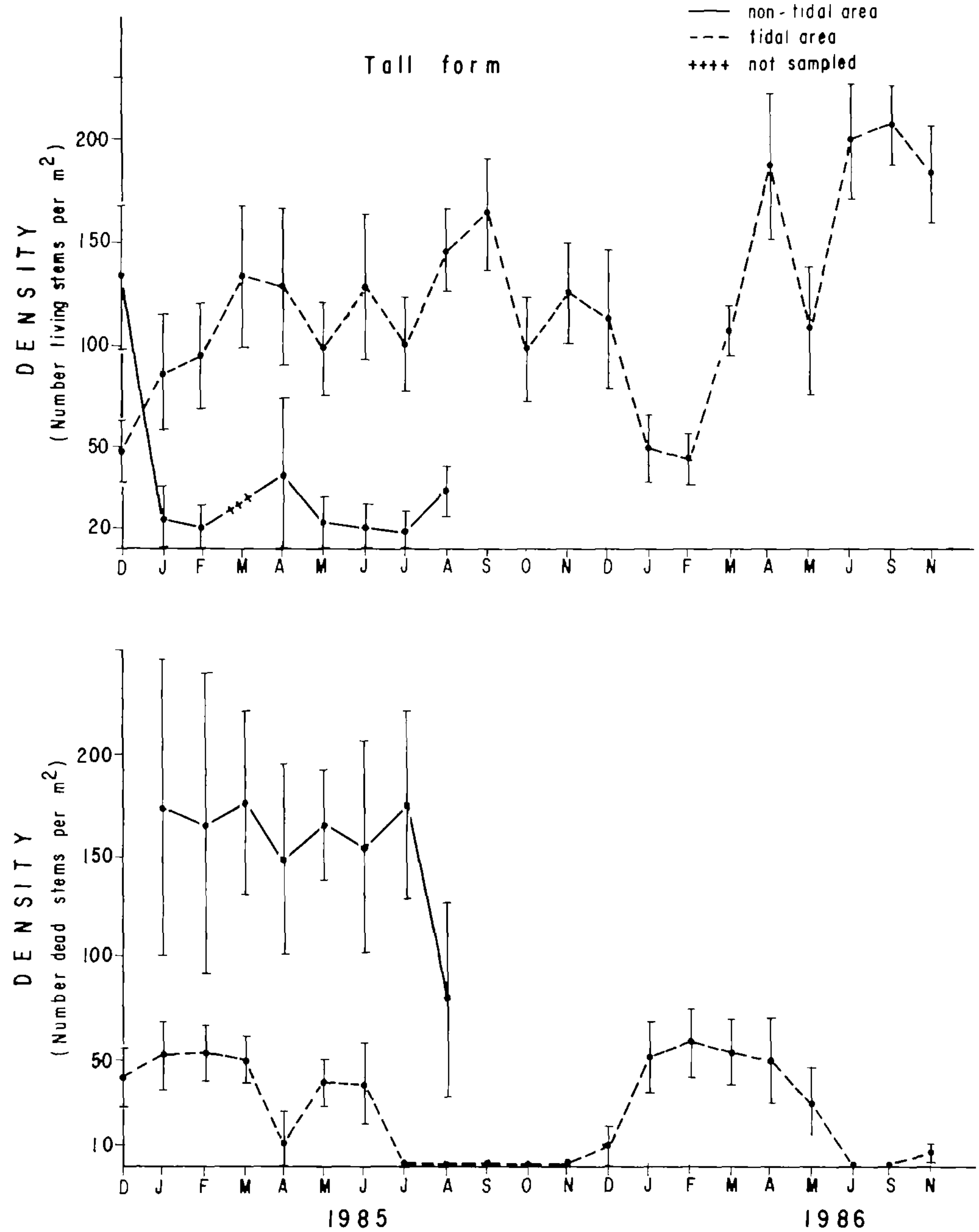

Fig. 8. Density of dead and living *S. foliosa*, tall form, stems in both tidal and non-tidal areas. No living stems remained in the non-tidal area after August 1985 (top). The lack of dead stem values during the same time period (bottom), indicates that all the dead stems became part of the litter. Bars represent ±1 SE.

cm depth. Percent soil moisture (gravimetric method) was assessed from the top five centimeters collected with a scoop. Numbers of living and dead *S. foliosa* stems and average height were calculated on the basis of five random stems per quadrat (Zedler 1983; Zedler and Nordby 1986). For all variables, monthly averages were calculated from the ten sampled quadrats. Total stem length of *S. foliosa* was

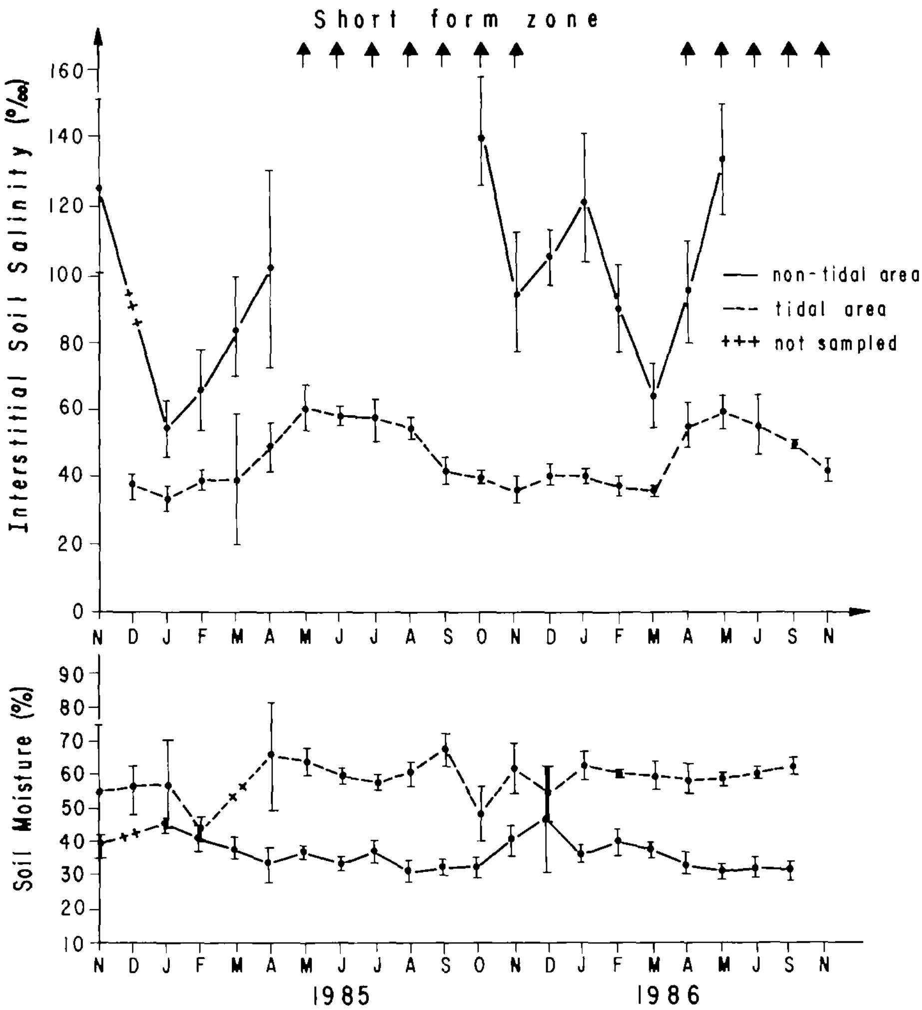

Fig. 9. Sediment physical characteristics at the short *S. foliosa* zone. Top figure represents interstitial soil water salinity. Arrows indicate values off scale. Bottom, percentage soil moisture for both areas. Bars represent ± 1 SE.

calculated by multiplying average monthly shoot density by average monthly height (Zedler *et al.* 1986). Values are expressed as m m^{-2}.

Middle marsh vegetation. Each month, twenty 0.25 m^2 circular quadrats were placed randomly as described above. In each quadrat, soil moisture and interstitial soil water salinity were measured. Percentage cover of living and dead species was estimated, using a seven-class system (0%, 1%, 2-5%, 6-25%, 26-50%, 51-75%, 76-100%). Average percentage cover was calculated from midpoints of the cover classes. Percent frequency of occurrence was calculated from the total number of quadrats sampled during the study period.

Statistical analyses. Statistical tests included: t-test to compare average salinity values between sites at each marsh level; two-way (time and sites) non-parametric ANOVA, to compare percent soil moisture values for the different marsh levels; and Kruskal-Wallis test to analyze interannual variation. A t-test was also used to test differences in shoot density and total stem length of *S. foliosa* between sites. This analysis covered only the time period in which living and dead stems were standing.

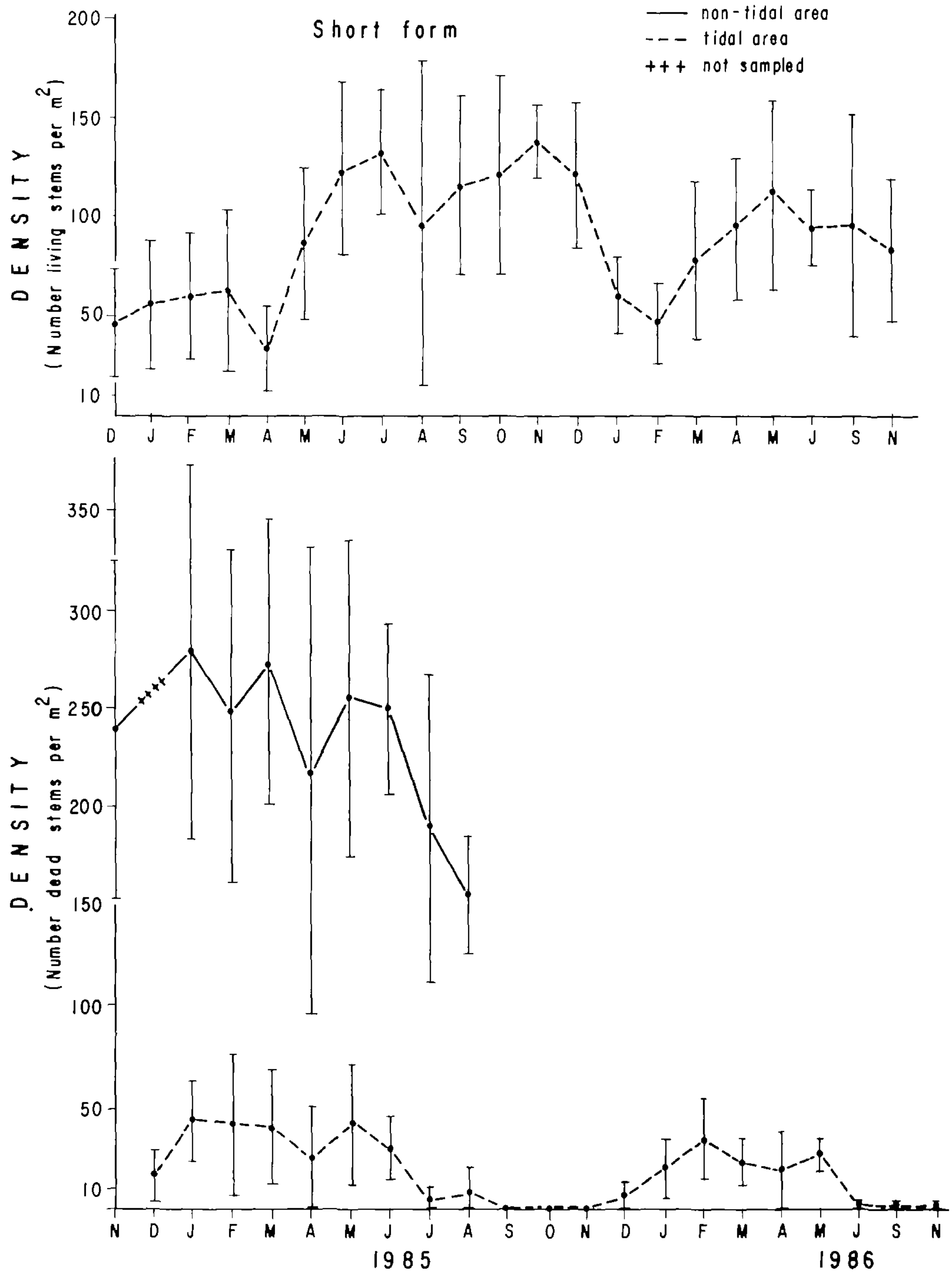

Fig. 10. Density of living and dead *S. foliosa*, short form, stems. Top figure represents living stems which were found only in the tidal area. Dead stems in the non-tidal area could only be evaluated until September 1985. Afterwards they became part of the litter (bottom figure). Bars represent ± 1 SE.

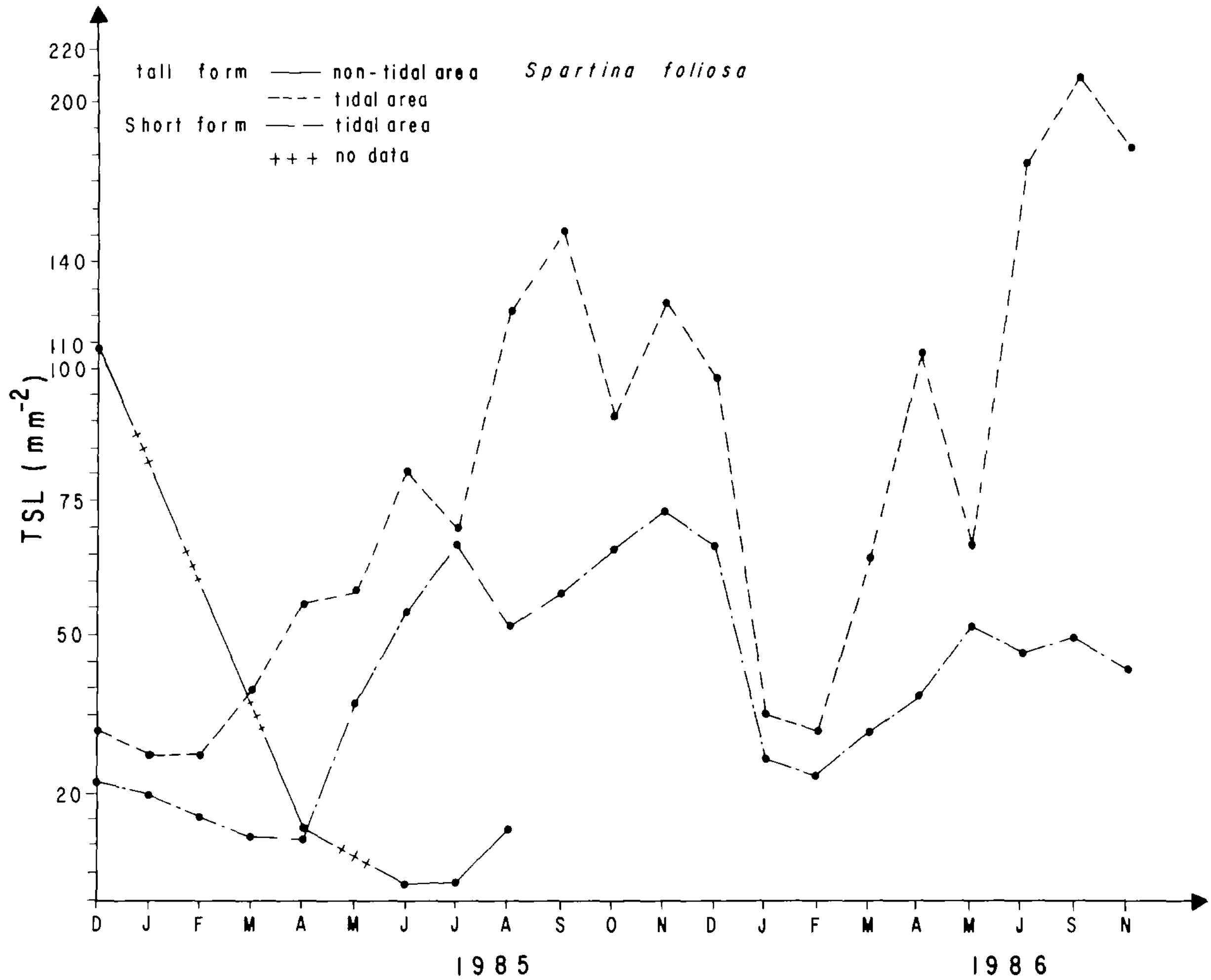

Fig. 11. Total stem values for both height forms in the two areas. No living stems of the short form were found in the non-tidal area.

Interstitial soil water salinity and percentage soil moisture in the middle marsh were analyzed as described above. The Shannon-Weiner diversity index was calculated for each month. T-tests were used to compare diversity indices and percentage cover per species between tidal and non-tidal areas. In all cases, the significance level was 0.05.

Results

The effects of drought were evident when we began our sampling, four months after the dike was completed. At the lower elevations, dead stems of *S. foliosa* were abundant and channels were dry. *Batis maritima* and *S. virginica* were already invading clearings left by *S. foliosa*. At higher elevations, sediments were white and cracked due to salt deposition and reduced moisture. Invertebrates associated with this vegetation were dead.

In the tall *S. foliosa* zone, interstitial soil water salinity increased to an average of 102 parts per thousand (ppt). This value underestimates the actual value because summer and end-of-sampling values exceeded the refractometer scale. In the tidal area, the average salinity was 43 ppt. The t-test indicated that these differences in soil salinity were highly significant ($p < 0.001$). Soil moisture averaged 45% in the tidal area and 38% in the non-tidal area (Fig. 7). The two-way ANOVA indicated sig-

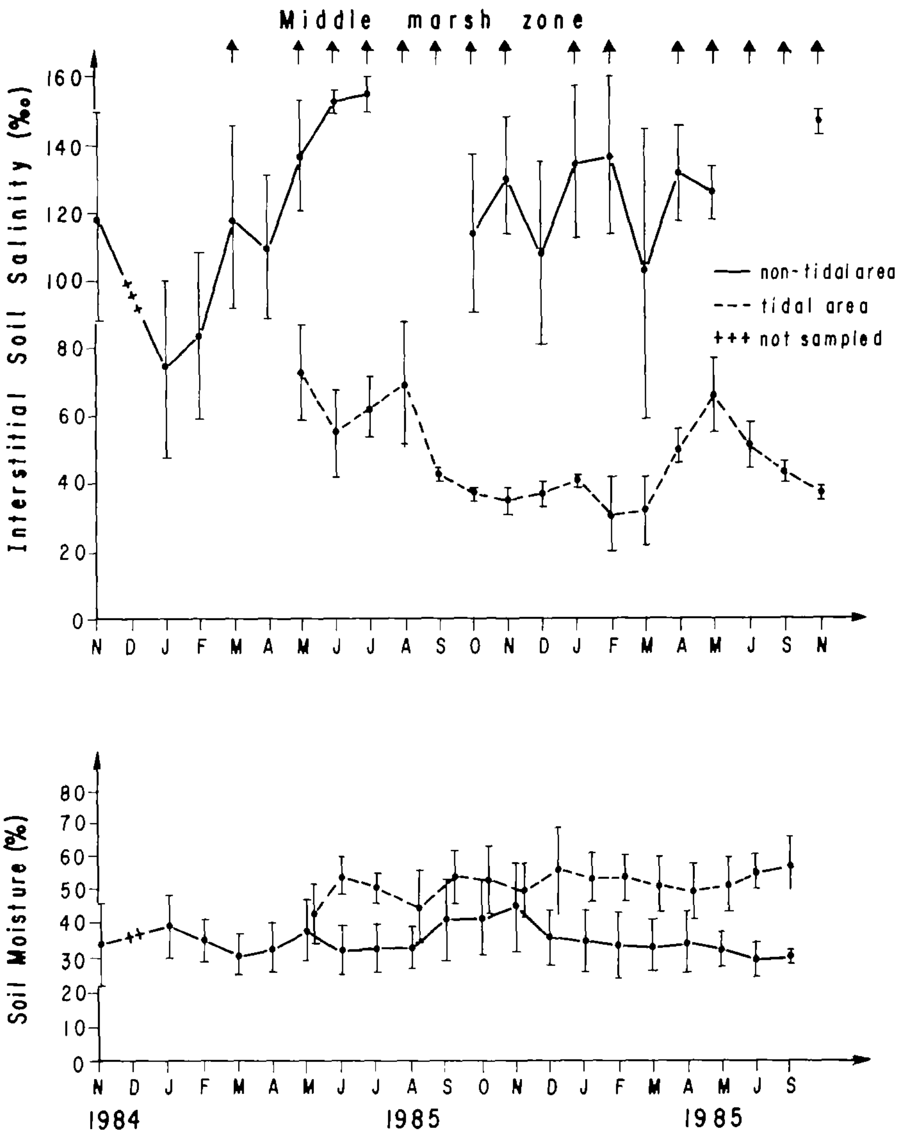

Fig. 12. Sediment physical characteristics in the middle marsh. Arrows indicate interstitial soil water salinity values exceeding the scale of the refractometer. Bars represent ± 1 SE.

nificant differences between tidal and non-tidal areas ($p < 0.001$), as well as a significant interaction between factors ($p < 0.001$). The Kruskal-Wallis test showed a highly significant difference between years only at the non-tidal area ($p < 0.001$), with sediments becoming slightly drier in the second year. In 1985, the average soil moisture at the non-tidal area was 38% while in 1986 it was 36%. The average densities of living stems were 120 and 32 stems m^{-2} for tidal and non-tidal areas, respectively, these differences being very significant ($p < 0.01$). Dead stems numbered 40 and 156 stems m^{-2}, respectively, a highly significant difference ($p < 0.001$). Dead stems became part of the litter after 9 months in the non-tidal area (Fig. 8).

In the non-tidal short *S. foliosa* zone, interstitial soil water salinity increased to an average of 98 ppt (underestimated) compared to 46 ppt in the tidal area, these differences being highly significant ($p < 0.001$). Soil moisture was statistically different ($p < 0.001$) between the two areas, with an average value of 59% in the tidal area, versus 36% in the

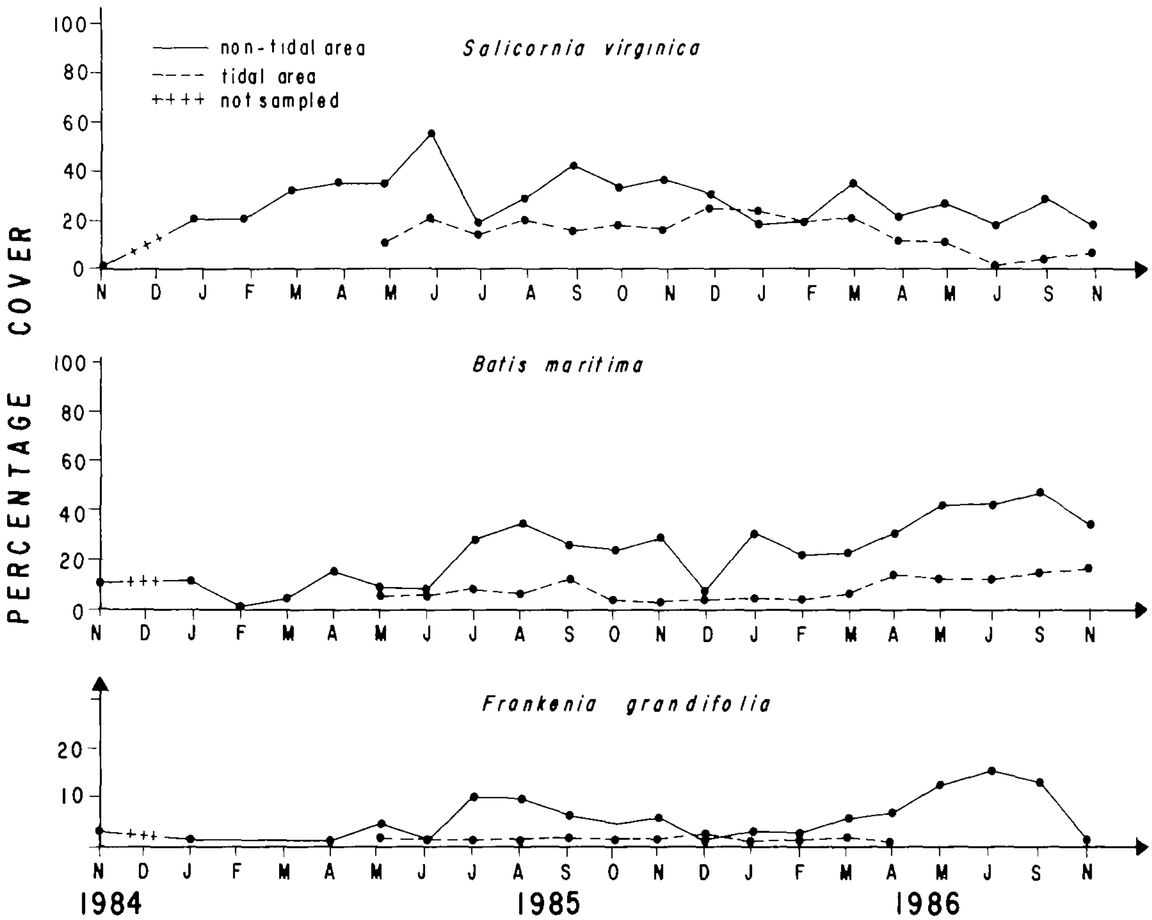

Fig. 13. Percent cover of the three most common middle marsh species after tidal exclusion. Percent cover increased in the non-tidal area, relative to the tidal area.

non-tidal area. Interannual variations were significant in both areas, with $p<0.02$ in the tidal area, and $p<0.001$ in the non-tidal area (Fig. 9). Only dead stems of the short form were found in the non-tidal area during the study period. The number of dead stems averaged 232 stems m^{-2} during the first ten months of sampling, while an average of 28 dead stems m^{-2} was found for the same time interval at the tidal area ($p<0.001$). After this period, all dead stems at the non-tidal area became litter (Fig. 10).

The response of *S. foliosa* to drought in the non-tidal area was rapid and noticeable. In December 1984, total stem length of the tall form was 108.2 m m^{-2}. During the following spring and summer months, low values were recorded until all stems became litter. Average total stem length in the tidal area, over the entire study period, was 88.6 m m^{-2} for the tall form zone and 41.5 m m^{-2} for the short form (Fig. 11). Differences in total stem length between these areas were significant ($p<0.01$).

Sediment characteristics in the middle marsh showed the same trend already described for the lower marsh. Interstitial soil water salinity inside the dike averaged 122 ppt (some values off scale), while outside the dike the average was 48 ppt. Again, the differences between areas were highly significant ($p<0.001$). Soil moisture was 52% and 35% in the tidal and non-tidal areas, respectively (Fig. 12). The two-way non-parametric ANOVA showed these differences to be significant ($p<0.001$), and the Kruskal-Wallis test indicated a very

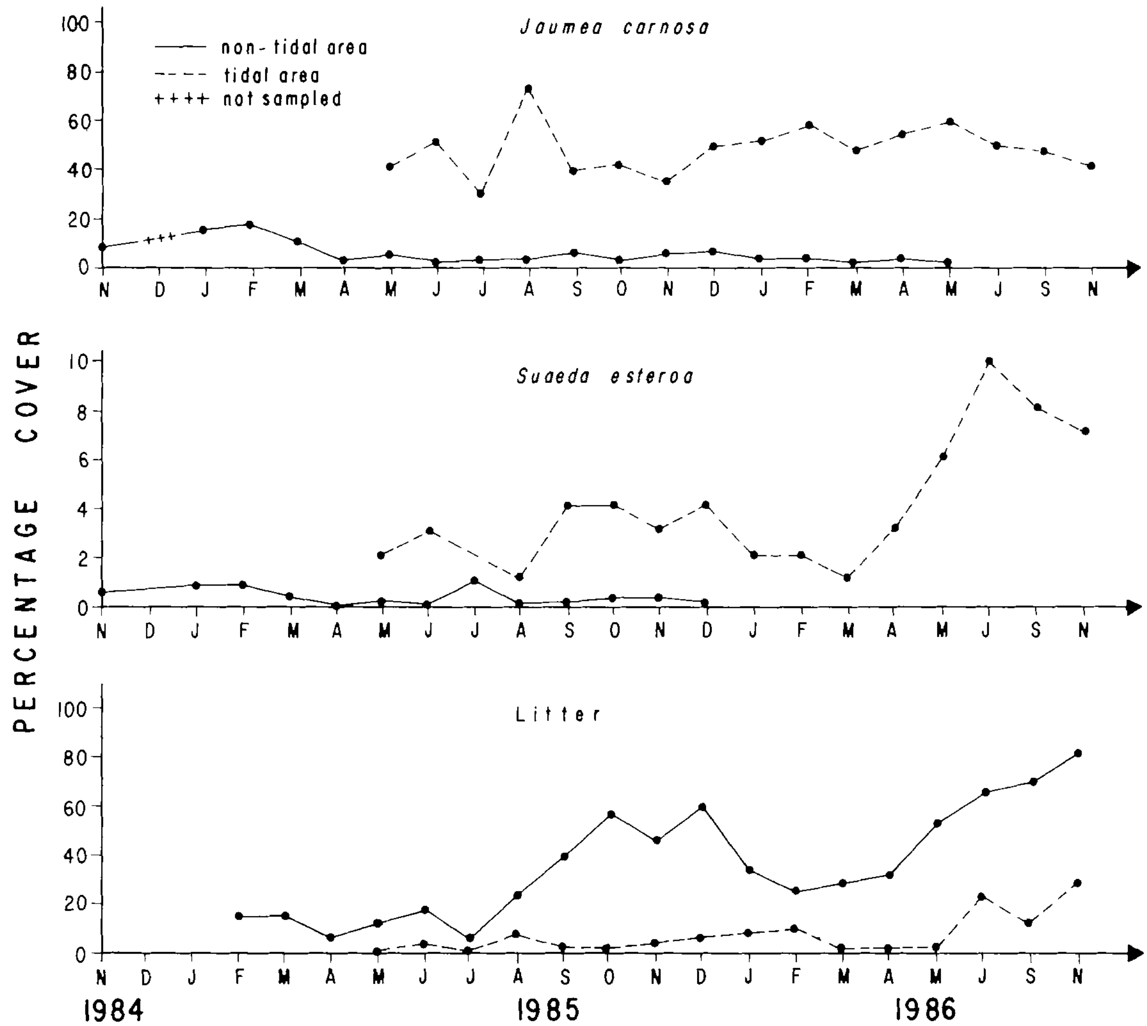

Fig. 14. Percent cover of two other remaining middle marsh species in the non-tidal and tidal areas. They persisted a year or more in the non-tidal area but disappeared before the end of the study. Bottom graph represents the increase in litter at the non-tidal area.

significant interannual variation in both tidal ($p < 0.001$) and non-tidal areas ($p < 0.01$). The amount of water available for middle marsh species was highly variable from year to year. Under natural conditions, water sources at this level are spring tides and rain. Inside the dike, rain and seepage water provided the moisture necessary for plant growth.

Drought favored the growth of *S. virginica* and *B. maritima*. For the first species, average percentage cover inside the dike increased to 29%, whereas in the tidal area average cover was 15%. For the second species, average percent cover was 23% inside the dike and 8% outside the dike. Of these two species, *S. virginica* was dominant during the first 8 months of the study (25% cover), but thereafter *B. maritima* increased in cover from 9 to 30%, so that, at the end of the sampling period, *S. virginica* and *B. maritima* were co-dominants (Fig. 13). Two other perennials persisted: *Frankenia grandifolia* (5% average cover) and *Jaumea carnosa* (4% average cover). The first species was present throughout the study period in the non-tidal area, with a higher percent cover inside the dike than in the tidal area (1% average cover). *Jaumea carnosa* disappeared from the non-tidal area in July 1986. In the tidal area, its percent average cover was 47% (Figs. 13 and 14).

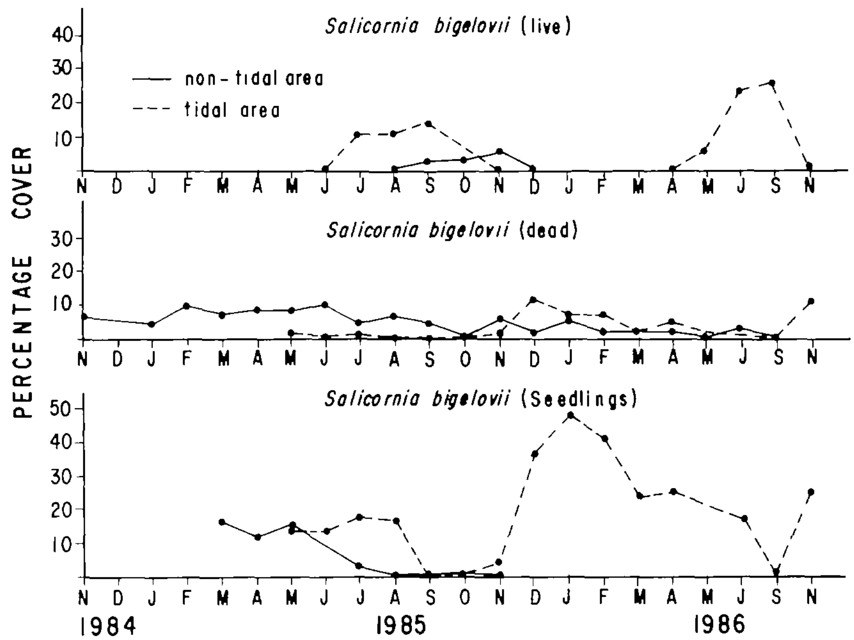

Fig. 15. Behavior of the annual species, *Salicornia bigelovii*, in both tidal and non-tidal areas of Punta Banda Estuary. Living plants and seeds were only seen the first year of sampling (1985) in the non-tidal area.

Table 1. Percent frequency values for middle marsh species at Punta Banda Estuary. Non-tidal area data represent average values for 22 months. Tidal area data represent average values for 16 months.

Species	Non-tidal area %	Tidal area %
Longer-lived perennials		
Salicornia virginica	86	83
Batis maritima	78	55
Jaumea carnosa	48	100
Frankenia grandifolia	41	18
Short-lived perennials		
Suaeda esteroa	11	39
Annuals		
Salicornia bigelovii	9	33

Of the annuals and short-lived species, only the most representative were sampled. The short-lived perennial, *Suaeda esteroa*, was completely eliminated from the non-tidal area (Fig. 14) as was the annual, *Salicornia bigelovii* (Fig. 15). *Salicornia bigelovii* seedlings were absent from the non-tidal area by the second year of the study (Fig. 15). Percent cover of litter at the non-tidal area averaged 30% over the course of the study while litter averaged 6% at the tidal middle marsh (Fig. 14).

Differences in percentage cover between both areas were significant for all species. In the case of *S. virginica*, *B. maritima*, *J. carnosa*, *S. esteroa*, seedlings of *S. bigelovii* and litter, these differences were highly significant ($p < 0.001$). For *F. grandifolia* a very significant difference was obtained ($p < 0.01$), and for living *S. bigelovii*, the difference was significant ($p < 0.05$).

Percent frequency data confirm the reduction of annual and short-lived perennial species and the dominance of longer-lived perennials (Table 1).

The average Shannon-Weiner diversity indices for the study period were 2.1 and 2.7 at the non-tidal and tidal areas, respectively. These values were significantly different ($p < 0.05$), indicating that middle marsh species diversity at the non-tidal area was reduced. At the non-tidal area, monthly diversity indices ranged from 1.4 to 2.8, while at the tidal area, values ranged from 2.5 to 3.0.

Discussion

Salinity has been identified as the controlling factor in salt-marsh vegetation patterns and the overriding stress on *S. foliosa* growth (Zedler *et al.* 1986; Zedler and Beare 1987). Hypersalinity explains its absence from wetlands that are frequently closed to tidal circulation (Zedler 1982).

Tidal exclusion in Punta Banda Estuary resulted in increased soil water salinity and significantly reduced soil moisture at both the lower and middle marshes. This led to the disappearance of *S. foliosa*, and a reduction of middle marsh species diversity. *Salicornia virginica* and *B. maritima* became co-dominants, and short-lived and annual species were eliminated.

These changes were similar to those observed in Tijuana Estuary. When this estuary was closed to tidal flushing for 8 months (April-November 1984), soil water salinity increased from 37 ppt (April) to 104 ppt (September). Substantial mortality of *S. foliosa* also occurred during this period, with the highest mortality rates found at the lowest elevations. *Salicornia virginica* became the dominant species in the middle marsh (Zedler and Nordby 1986).

From 1979 to 1982, *S. foliosa* average density at Tijuana Estuary was 54 stems m^{-2}, declining to 40 in September 1984. In Punta Banda, under tidal conditions, this species averaged 186 stems m^{-2} (peak season values for 1985-86). After a year of tidal exclusion in 1985, average density had declined to 28 stems m^{-2}, disappearing a year later. Average total stem length at Tijuana Estuary, prior to drought conditions (1979-82), was 55 m m^{-2}, decreasing to 45 by September 1984 (Zedler and Nordby 1986). In Baja California, values of 181 m m^{-2} were noted for the tidal area in 1985-1986, versus 14 m m^{-2} the first year and zero the second year in the non-tidal area. From this comparison, not only the greater density and height of *S. foliosa* stems in Punta Banda becomes evident, as an indication of a healthier habitat, but also the fact that vegetation response to drought was extreme in Punta Banda Estuary. The reason for this is that, in Tijuana Estuary, the mouth was bulldozed open in December 1984 to reestablish tidal flushing (Zedler *et al.* 1986), while drought conditions persisted in Punta Banda Estuary.

Soil moisture values in the lower marsh were similar for tidal and non-tidal areas, although significantly different from a statistical point of view (Figs. 7 and 9). Water within the dike apparently kept the lower marsh sediments moist. High soil salinity was thus the likely cause of *S. foliosa* mortality. The difference in soil moisture between the tidal and non-tidal areas of the middle marsh was greater than that of the lower marsh (Fig. 11).

Under dry, hypersaline conditions, *S. virginica* expands to the lower marsh (Zedler 1982; Brenchley-Jackson *et al.* 1987). At Punta Banda Estuary, *S. virginica* also expanded into areas previously occupied by *S. foliosa*. At higher elevations, dominance of longer-lived species has been attributed to their ability to extend their roots into the substate and use deeper water sources (Zedler 1982; Zedler and Nordby 1986).

A 61% average cover was reported for *S. virginica* at Tijuana Estuary during the 1984 non-tidal drought (Zedler and Nordby 1986). In this study, a lower percentage cover value for this species was found (29%) after two years of sampling, but dominance was shared with *B. maritima* (23%).

In October 1986, after 2 years and 6 months of construction, labor in the industrial area slowed (the study site had not been dredged). We were able to visit the site again in September and October 1988 and characterize longer-term vegetation responses. The dominant species within the diked area were *B. maritima*, *S. virginica* and *F. grandifolia*. Water within the dike allowed the persistence of some patches of *S. foliosa* at the shoreline of the old lower marsh. Although these patches were located at the tall form zone, their height was reduced and equivalent to the short form (average 57 cm). Evidence of flowering was also found. At Bolsa Chica Bay, California, Eilers (1980) attributed the persistence of *S. foliosa* for 80 years without tides to water seepage through the permeable beach sands.

Both the changes observed in percent cover of middle marsh species and the persistence of *S. foliosa* indicate that the community has not yet stabilized. Connell and Sousa (1983) have pointed out the importance of using appropriate scales of time and space to observe the response of populations before judging stability or persistence. They mention that "the minimum time period is at least one complete turnover of all individuals, including discrete colonies or clones". In our case, it would seem that two years of sampling was not long enough to judge stability or persistence. We would have predicted the elimination of *S. foliosa* from the study area, while we now know that at least some patches have persisted for 4 years.

Development pressure is extremely high on Baja California wetlands. When our study began, the industrial project was the only estuary modification. During 1987 a tourist hotel was developed on the sand bar north of the dike, and permits to build a marina on the estuary side were submitted. Of the 21 km^2 covered by the estuary, 2.2 km^2 have been modified at present (September 1989). This year a project to transform the whole estuary into a tourist resort was presented.

While we agree that increased revenue is an urgent need for México, development policies should allow a number of estuaries to remain in their natural state. In those estuaries where development is permitted, activities should be planned with the best available information on environmental impacts.

In México there is no tradition of involvement of the scientific community in public policy decisions. Exceptions are specific projects financed by governmental agencies such as the Federal Electricity Commission. However, environmental awareness has increased, as evidenced by the creation of a federal ecology agency in 1983 (Secretaría de Desarrollo Urbano y Ecología). Our information on the salt marsh vegetation of Punta Banda Estuary should be useful to planning efforts in two ways: it documents the botanical resources of the estuary, and it shows how tidal exclusion changes species composition. Additional studies that characterize the functional value of the marsh for the food web are urgently needed.

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