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Land Subsidence in Drained Histosols and Highly Organic Mineral Soils of California

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ABSTRACT

This study was conducted to determine historical trends in subsidence in the Sacramento–San Joaquin Delta and their environmental controls. Historical subsidence was determined by measuring soil surface elevation loss near electrical tower foundations and by evaluating survey data between 1922 and 1981. The data indicated that subsidence slowed with time. In the western Delta, average subsidence rates were 2.3 cm yr^{-1} from 1910 to 1988 and 1.5 cm yr^{-1} from 1952 to 1988. Spatially variability in subsidence was correlated with organic matter content of the soil (r^2 = 0.62), which in turn was related to the depositional and drainage history of the Delta. Subsidence rates appeared to be independent of crops grown.

AGRICULTURAL DRAINAGE of Histosols is common throughout the world and often leads to significant soil subsidence (Stephens et al., 1984). This subsidence can be accelerated if crop residue is burned after the harvest for pest and weed control or nutrient augmentation. The environmental problems associated with soil subsidence are both small scale and large scale in extent. Soil subsidence can greatly increase the potential for agricultural lands to be subject to flooding and poor drainage. On a global scale, the soil organic matter lost by oxidation and combustion of C can significantly contribute to the amount of CO_2 in the atmosphere (Armentano, 1980; Rojstaczer and Deverel, 1993). The Sacramento–San Joaquin Delta has long been known as an area undergoing soil subsidence (e.g., Weir, 1938). Average rates of soil subsidence in the region are among the highest in the world (Stephens et al., 1984). While soil subsidence and its environmental influences have been examined in detail in the Florida Everglades, little work has been done on examining the amount and causes of temporal and spatial variability of subsidence in other regions.

Soil subsidence in the Delta has been documented by several other workers (Weir, 1938, 1950; Broadbent, 1960; Prokopovitch, 1985; Rojstaczer and Deverel, 1993). Much of this work has been concerned with quantifying rates of subsidence in the region. Some laboratory research has been performed on Delta soils which shows that oxidation rates are strongly controlled by temperature and weakly controlled by soil moisture content under unsaturated conditions. Little research, however, has examined the causes of variations in the rate of Delta subsidence over time and space. This study examined historical trends in subsidence in the Delta and their environmental controls. Spatially variable and time-averaged subsidence rates were estimated by measuring elevation loss at electrical transmission towers installed in 1910 and 1952 and leveling surveys done from 1922 to 1981. We examined the influence of agricultural practices on subsidence rates. We also examined the influence of sediment depositional environment and soil C content on subsidence.

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MATERIALS AND METHODS

Description Of Study Area

Figure 1 shows the location and geographic features of the Sacramento–San Joaquin Delta. The Delta is at the confluence of the Sacramento and San Joaquin rivers and smaller rivers entering the Delta from the east. About 80% of modern Delta inflow comes from the Sacramento River (Prokopovitch, 1985). Intertidal organic deposits began to accumulate in the Delta

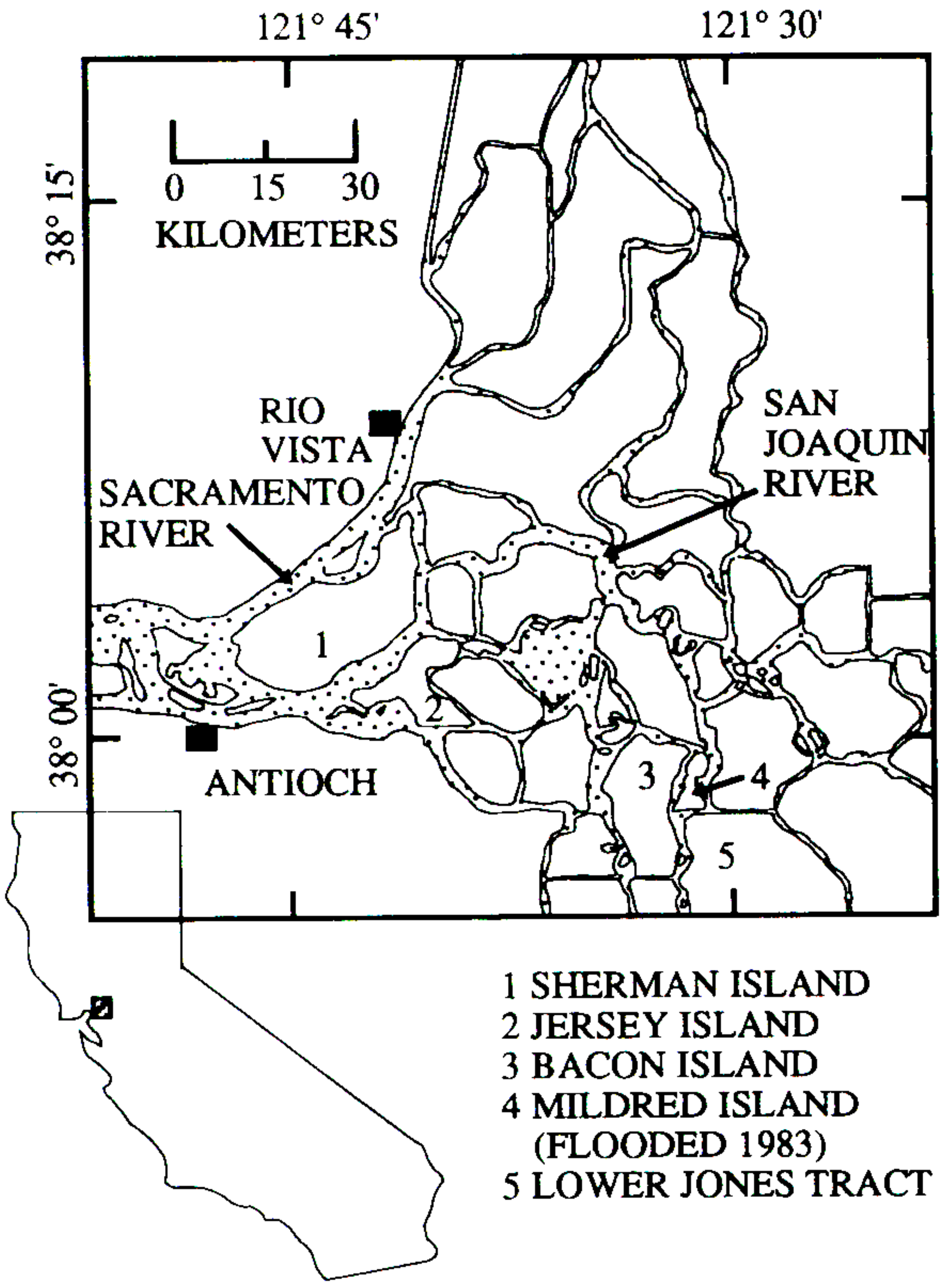


Fig. 1. Location and geographic features of the Sacramento–San Joaquin Delta.

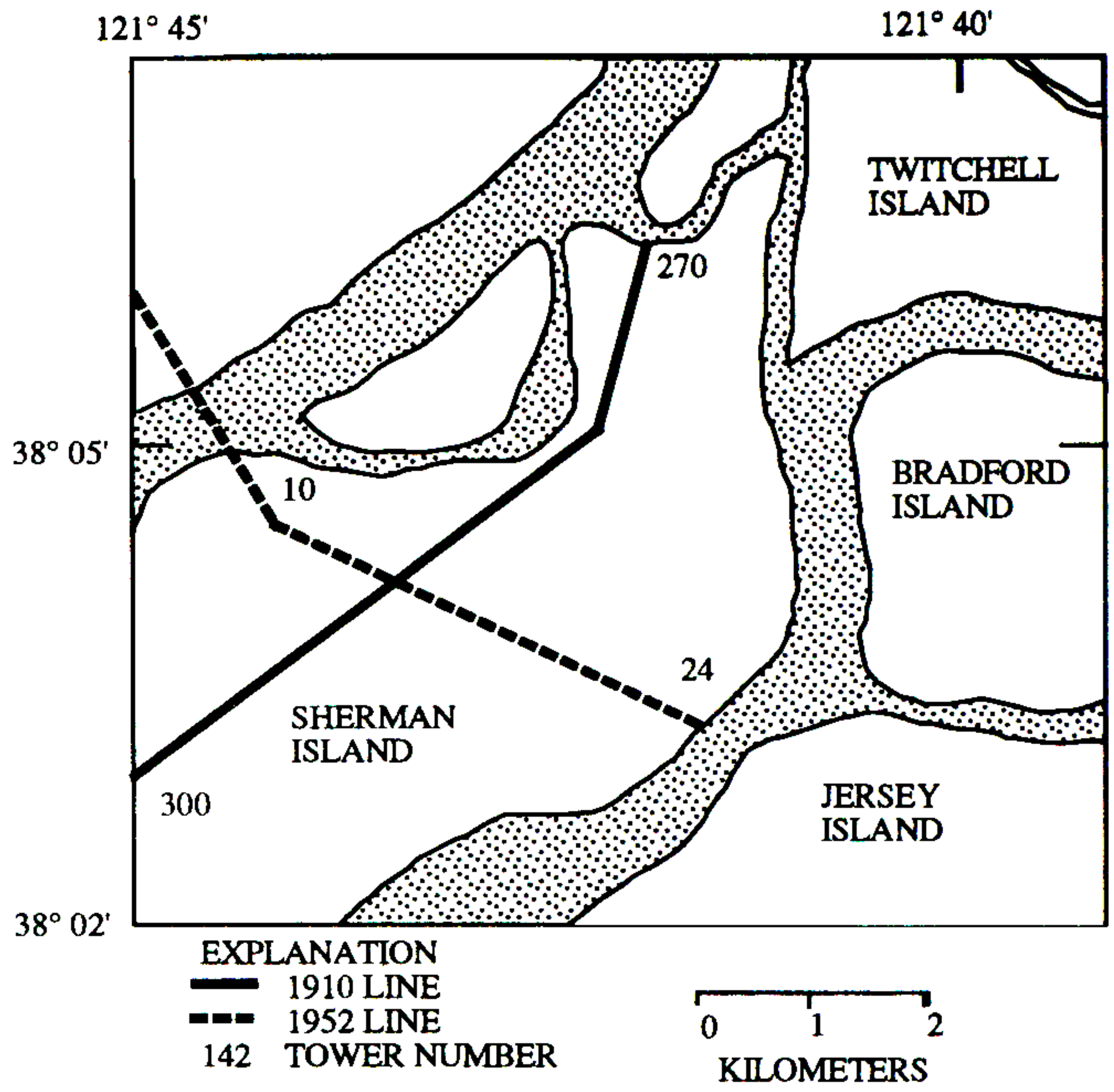


Fig. 2. Locations of 1910 and 1952 electrical transmission power lines.

about 7000 yr ago (Shlemon and Begg, 1975). Intertidal deposits spread across pre-Holocene alluvial and eolian deposits in the Delta as the result of the Holocene rise in relative sea level. This sea-level rise began to affect deposition in the Delta between 11000 and 7000 yr ago (Atwater et al., 1977). The organic sediments were derived primarily from the decomposition of tules, bulrushes (*Scirpus* spp.) and reeds (*Phragmites* spp.) (Atwater, 1980).

Before the California Gold Rush of the 1850s, the Delta was composed of about 1,400 km^2 of marshes and swamps that were subjected to tidal inundation (Gilbert, 1917). Beginning in the latter part of the 19th century, levees were constructed and the area was drained for agriculture. The Delta took on its current form by the 1930s, when drainage of 100 islands and tracts and construction of about 2250 km of levees was completed (Thompson, 1957). Water levels on the islands generally are now maintained at 1 to 2 m below land surface by networks of drainage ditches.

Drainage has caused the organic soils to oxidize and subside. Land-surface elevations of the leveed islands are now significantly below sea level (California Department of Water Resources, 1980, 1986). Several studies have made estimates of subsidence rates in the Delta. Historical rates range from 2.8 to 11.7 cm yr^{-1}, with the higher rates generally associated with the central Delta (Weir, 1950; Prokopovitch, 1985; California Department of Water Resources, 1986). Rojstaczer and Deverel (1993) showed that mean annual subsidence rates of the three islands examined by Weir (1938, 1950) have slowed with time.

The USDA Soil Conservation Service (unpublished preliminary maps of the region) described five soil regimes in the Delta: (i) Sacramento River deltaic deposits deposited prior to the 1850s and deposited onto peat because of hydraulic mining after the 1850s; (ii) deep organic soils in the middle of the Delta; (iii) soils developed in saline intertidal areas; (iv) soils developed from fluvial silts and clays along the eastern border of the Delta; and (v) soils developed from the San Joaquin River deltaic deposits.

In the western Delta, islands bordering the Sacramento River are composed of soils that primarily are mineral, mineral–organic complexes, and organic. The soils on these islands are predominantly organic toward the center and eastern parts of the island. The soils in the western parts and on the margins of the islands generally are mineral and mineral–organic associations. Islands in the central Delta are composed almost entirely of organic soils.

In general, strictly mineral soils occupy a network of mineral ridges along major, naturally occurring streams. Along the slopes of these streams, the lower positions are occupied by an admixture of fine-textured mineral sediments and organic matter. In the low-lying areas in the center of the islands, organic soils predominate (Cosby, 1941). Because of the higher organic matter content of the soils in the interior of the islands, many of the islands have developed a saucer shape, apparently because of the greater subsidence where organic matter contents are higher (Thompson, 1957). Cosby (1941) reported values ranging from 33 to 83% organic matter for organic soil samples collected during the 1930s.

Methods for Evaluating Changes in Land-Surface Elevations

In the western Delta, changes in land-surface elevation relative to electrical transmission tower foundations were measured by positioning a level in the field adjacent to each of the four foundations supporting the tower. The measurements were made during July 1988. The average of the four measurements was compared with the average foundation heights of the towers when they were first constructed. Locations of the 1910 and 1952 electrical transmission power lines on Sherman Island are shown in Fig. 2. Historical foundation heights were obtained from blueprints provided by Pacific Gas and Electric Company. For the 1910 power lines, a generalized blueprint applicable to all tower foundations was available. The foundations were intended to be installed with 60 cm of concrete exposed above the land surface. Errors in measurement for the 1910 data probably are about ±30 cm because of the possibility that foundation installation was different from the blueprint. The error associated with the 1952 data is less than the error associated with the 1910 data because the blueprints for each foundation showed the land-surface elevations relative to the foundation during construction. Measurements were made at most foundations along the transects shown. Some foundations were not measured because of inaccessibility or because the original foundations had been replaced since the 1910 and 1952 installations.

To evaluate land subsidence in the central Delta, we examined transect surveys on Bacon Island, Lower Jones Tract, and Mildred Island following the route shown in Fig. 3. The surveys were conducted between 1922 and 1981 (Weir, 1950). Field notes for all the surveys were obtained from the California Department of Water Resources (Begg and Carlton, 1981, unpublished data). Most of the field notes contained information about the crops grown along the transect. Closure difference for the surveys ranged from 1.2 to 12.8 cm. Weir (1950) considered a closure error of 9.1 cm acceptable due to the difficult leveling conditions. We assumed that the error was randomly distributed along the 13.3-km survey transect. Surveys were referenced to a benchmark on the levee at the southwest corner of Lower Jones Tract.

Soil samples were collected adjacent to the foundations on Sherman Island in 1990 at depths of 30 and 60 cm. These depths were selected so that samples would be below the depth of active tilling and near the maximum elevation of the water table. The organic matter content of all soil samples was determined by residue loss on ignition at 550°C.

RESULTS AND DISCUSSION

Subsidence Estimated from Electrical Transmission Tower Foundations

We estimated historical subsidence by measuring changes in land-surface elevation in July 1988 at tower foundations constructed in 1910 and 1952. The measurements at the foundations serve as subsidence estimates because they are mounted on pilings that were driven to refusal below the organic soil layer. We evaluated spatially variable subsidence rates in relation to the distribution of soil types, organic matter content of soil, and the locations of the foundations. The total amount of subsidence estimated from measurements of towers constructed in 1910 and 1952 are shown in Fig. 4. In our subsidence estimates, we assumed that the tower foundations have not changed in elevation with time.

On Sherman Island, the foundations were increasingly exposed toward the center of the island, showing a maximum amount of subsidence of 240 cm from 1910 to 1988. For the data from the towers constructed in 1910, the median subsidence rate on Sherman Island was 2.3 cm yr^{-1}. Data from the towers constructed in 1952 indicate a maximum amount of subsidence of 122 cm and a median subsidence rate of 1.5 cm yr^{-1}. Comparison of the 1910 and 1952 tower elevations suggests that the rate of subsidence is slowing with time. The rate calculated from the 1952 towers is significantly lower ($\alpha = 0.01$) than the rate calculated from the 1910 towers, as determined by the Wilcoxon rank sum test (Hollander and Wolfe, 1973). The apparent slowing in subsidence rate may also be attributable to differences in organic content between the soils encountered along the 1910 and 1952 towers.

We assessed the spatial variability in subsidence on Sherman Island by evaluating the amounts of subsidence

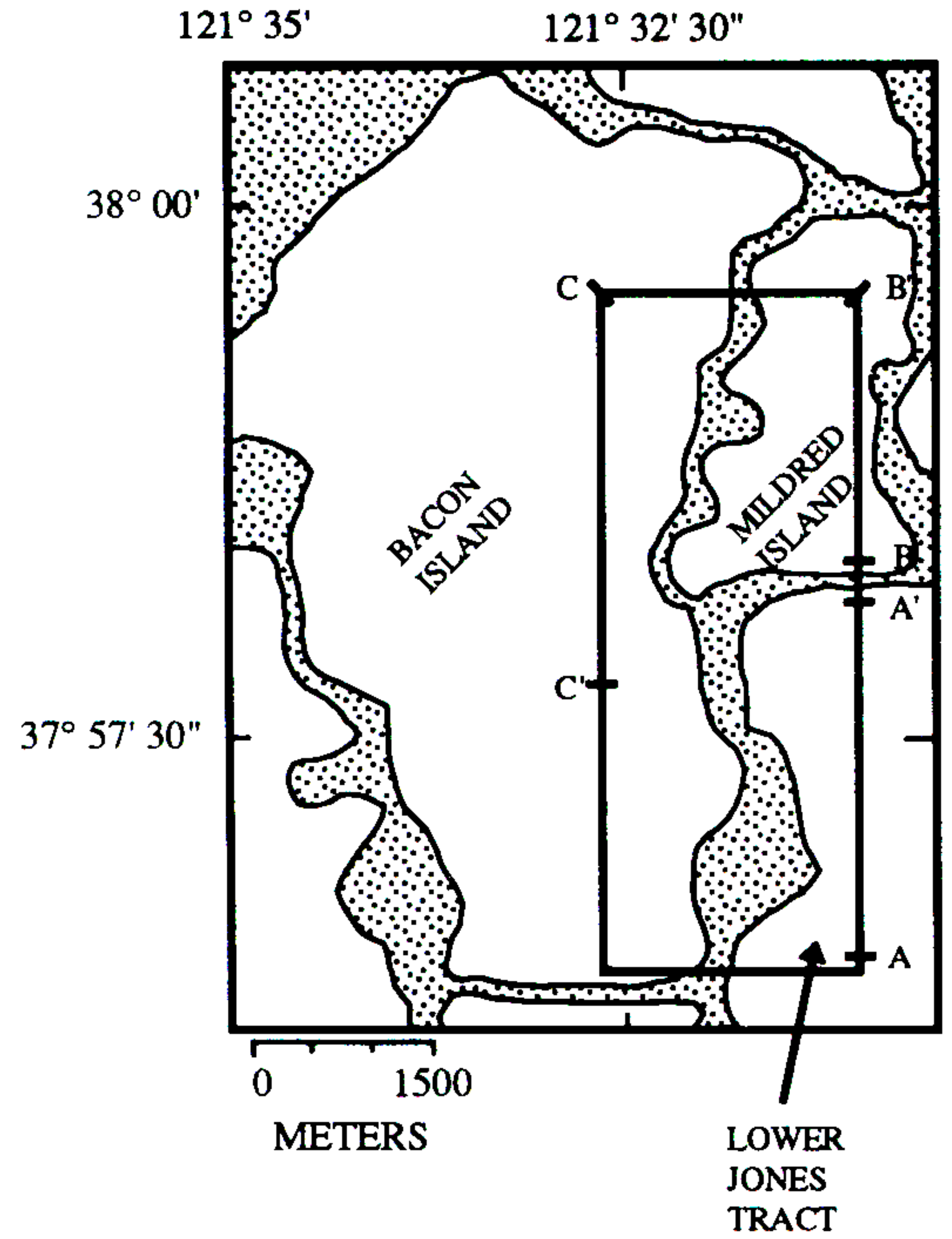


Fig. 3. Location and route of transect survey (Weir, 1950) and location of sections shown in Fig. 6.

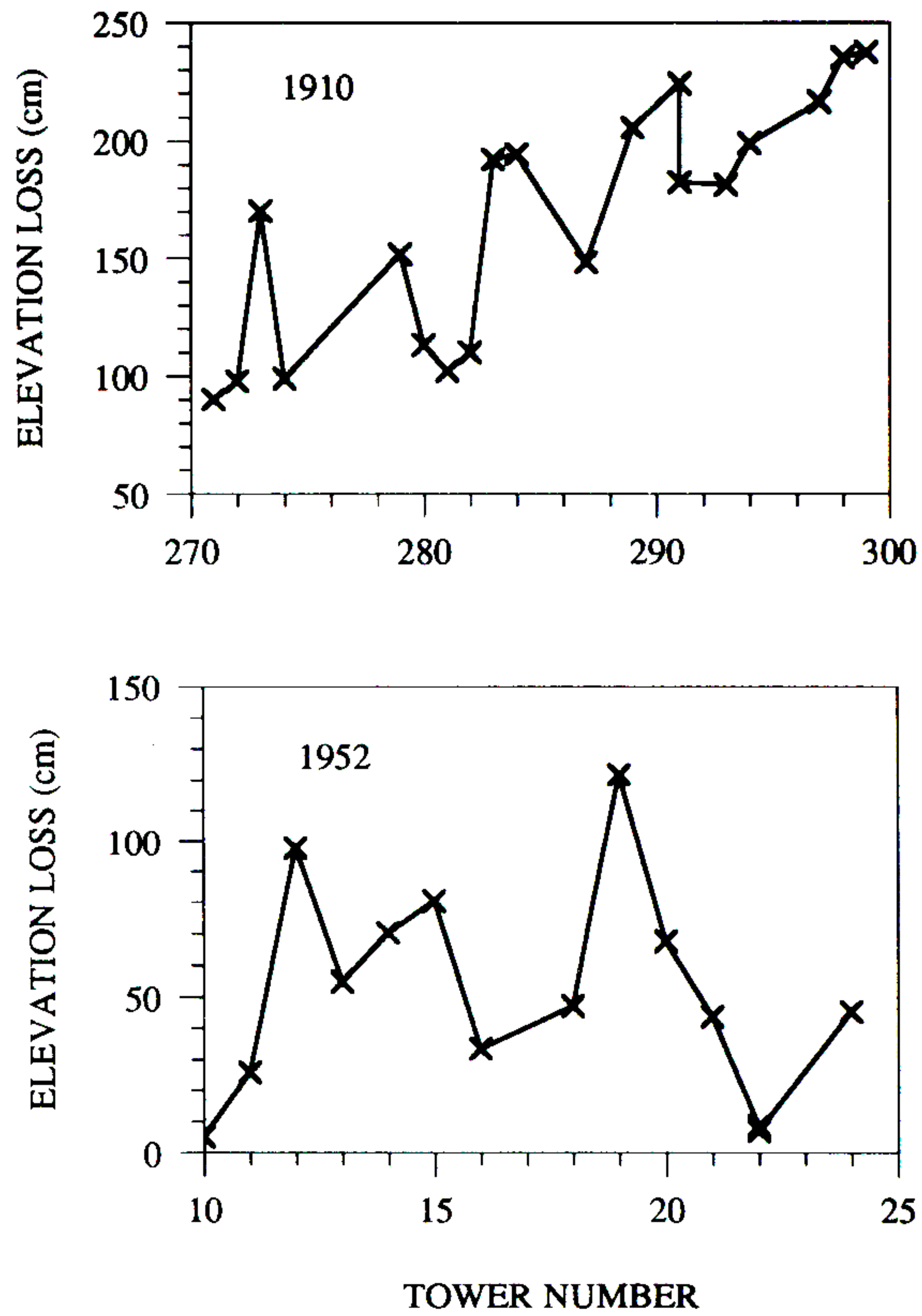
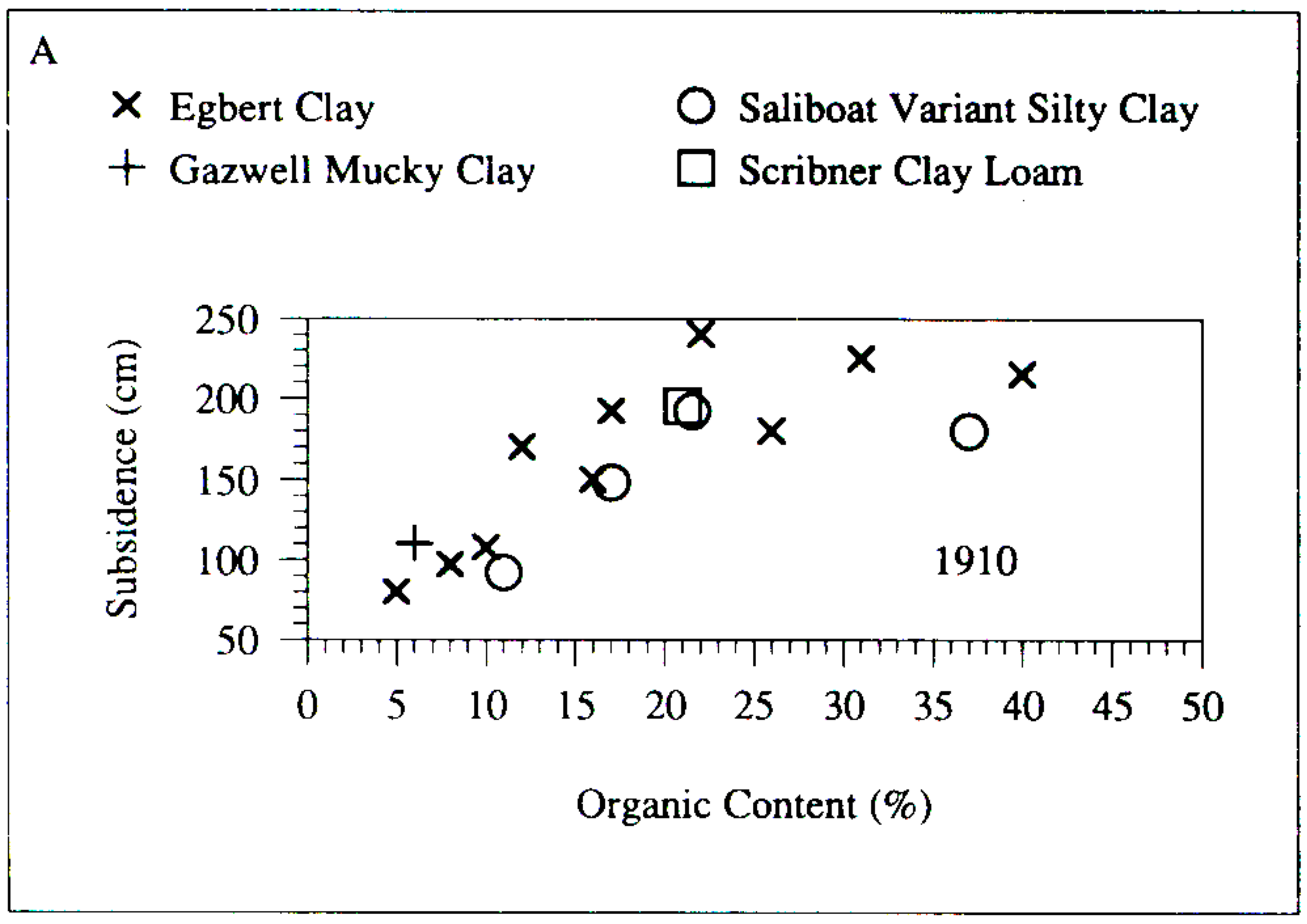


Fig. 4. Cumulative average amount of subsidence as of July 1988 at electrical transmission towers since 1910 and 1952. Locations of transmission lines shown in Fig. 2.

in relation to the organic matter content of soil, the soil type adjacent to the tower foundations, and the distance of the foundation from the levee. For the 1910 foundation data, subsidence rates for the different organic matter contents were <20% organic matter, 0.64 to 2.16 cm yr^{-1}; 20 to 30% organic matter, 1.00 to 3.02 cm yr^{-1}; and >30% organic matter, 1.54 to 2.85 cm yr^{-1}. For the 1952 foundation data, organic matter contents ranged from 14 to 48% and subsidence rates ranged from 0.19 cm yr^{-1} at the site with 14% organic matter content to 2.26 cm yr^{-1} at a site with 48% organic matter. It should be noted that the organic matter content of the soil was significantly higher at the time of the 1910 tower installation.

Figure 5a shows the relation of the mean organic matter content of the samples collected at the 30- and 60-cm depths adjacent to the 1910 foundations to the estimated subsidence. It should be noted that there is generally a poor correlation between the organic matter content of the soils as defined by soil taxonomy and the mapped soil types and no trends in organic matter content with depth were observed. The organic matter content is significantly correlated ($\alpha = 0.01$) with subsidence and explains 62% of the variance. Samples with the highest organic matter content were collected farthest from the levees, whereas the samples with the lowest organic matter content were collected closest to the levees.



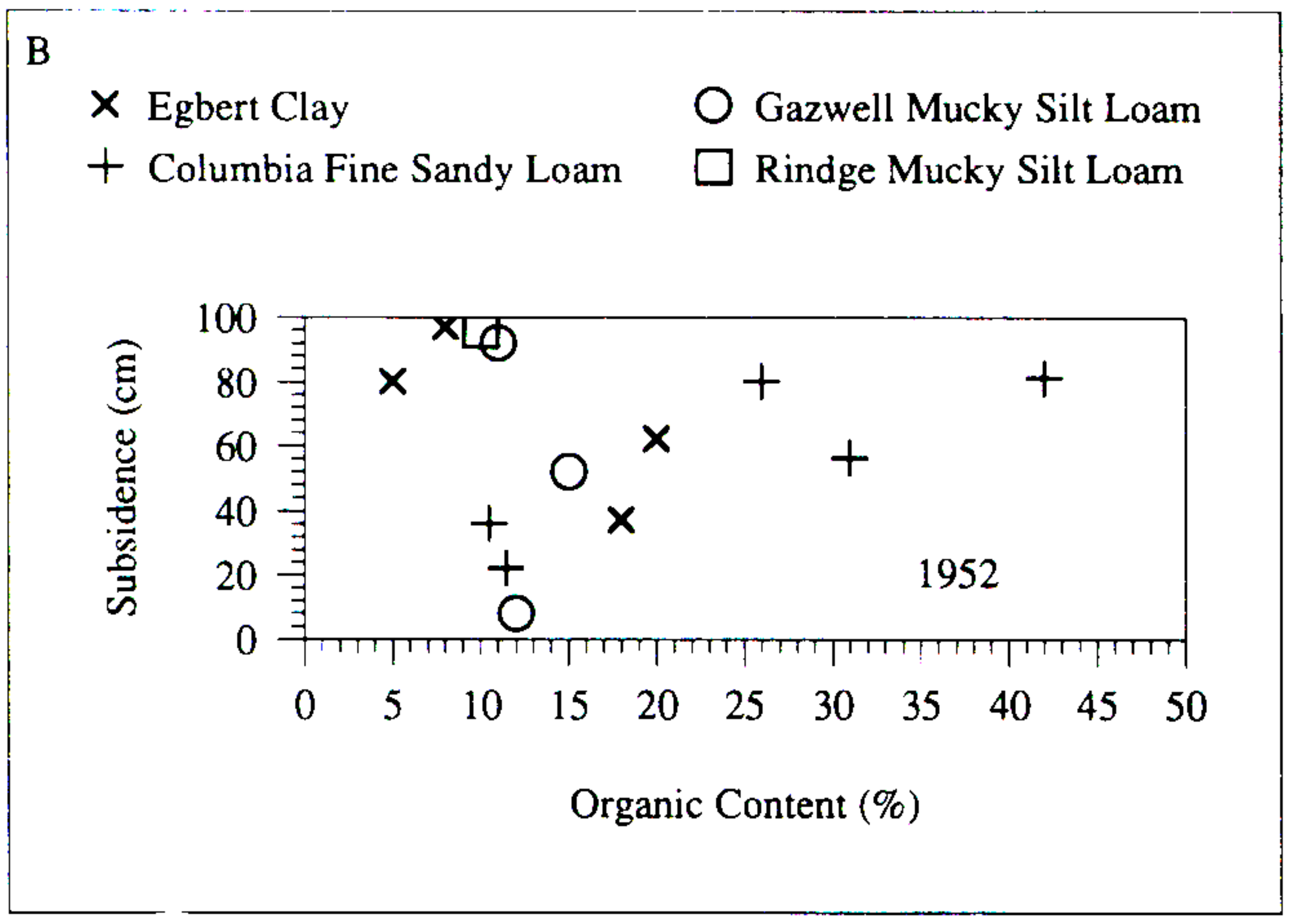


Fig. 5. Relation of average amount of subsidence and average organic matter content of soil in 1990 at electrical transmission towers of (A) 1910 and (B) 1952. Note that there is generally a poor correlation between the organic matter content of the soils as defined by soil taxonomy and the mapped soil types.

Figure 5b shows the relation of the organic matter content and the amount of subsidence for the 1952 foundation data. Organic matter content generally increased with increasing subsidence, except for one location where subsidence was substantial but organic matter was low. The soil series at this location is associated with (overlying or underlying) organic soils. This soil may have been overlain by organic soils that completely oxidized.

The distribution of soil series on Sherman Island is consistent with the spatially variable subsidence and the distribution of organic matter contents of soil and reflects the island's depositional history. The organic soils, Rindge mucky silt loam (euic, thermic Typic Medisaprist) and Gazwell mucky silt loam (fine, mixed, thermic Cumulic Haplaquoll), predominate in the center of the island with organic matter contents ranging from 10 to 50%. Mineral soils, Columbia fine sandy loam (coarse-loamy, mixed, nonacid, thermic Aquic Xerofluvent) and Egert clay (fine, mixed, thermic Cumulic Haplaquoll), probably deposited as natural levees, predominate along the edges of the island. These two soils also predominate where there was a levee break near the turn of the century (Thompson, 1957). The organic–mineral associations, Sailboat variant silty clay (fine-loamy, mixed, nonacid, thermic Aquic Xerofluvent) and Scribner clay loam (fine-loamy, mixed, thermic Cumulic Haplaquoll), primarily are in areas downslope of the natural levees and tend to be confined to narrow channels. As a result of being on the western edge of the Delta (Fig. 1), Sherman Island has been subject to deposition from the Sacramento and San Joaquin rivers. This is reflected in the variability in soil series. Subsidence and organic matter contents of soil are the lowest near the levees because of fluvial deposition of mineral material. Higher organic matter contents toward the center of the island resulted in greater subsidence.

Subsidence Estimated from Leveling Surveys

Subsidence measured by leveling along the transect shown in Fig. 3 began in 1922 (Weir, 1950). In an earlier study, we examined mean annual subsidence rates for each of the three islands included in the transect and noted that mean annual subsidence rates have declined with time (Rojstaczer and Deverel, 1993). In this study, we examined the transect data for temporal and spatial trends in subsidence relative to cropping patterns. The California Department of Water Resources (1980) indicated that different agricultural practices associated with different crops could affect local subsidence rates, but they were not able to confirm this with available data. Where practiced, they estimated that burning of soil organic matter could result in 0.2 to 0.3 cm yr^{-1} of subsidence.

Subsidence histories were constructed for each of the islands along the transect. To construct subsidence histor-

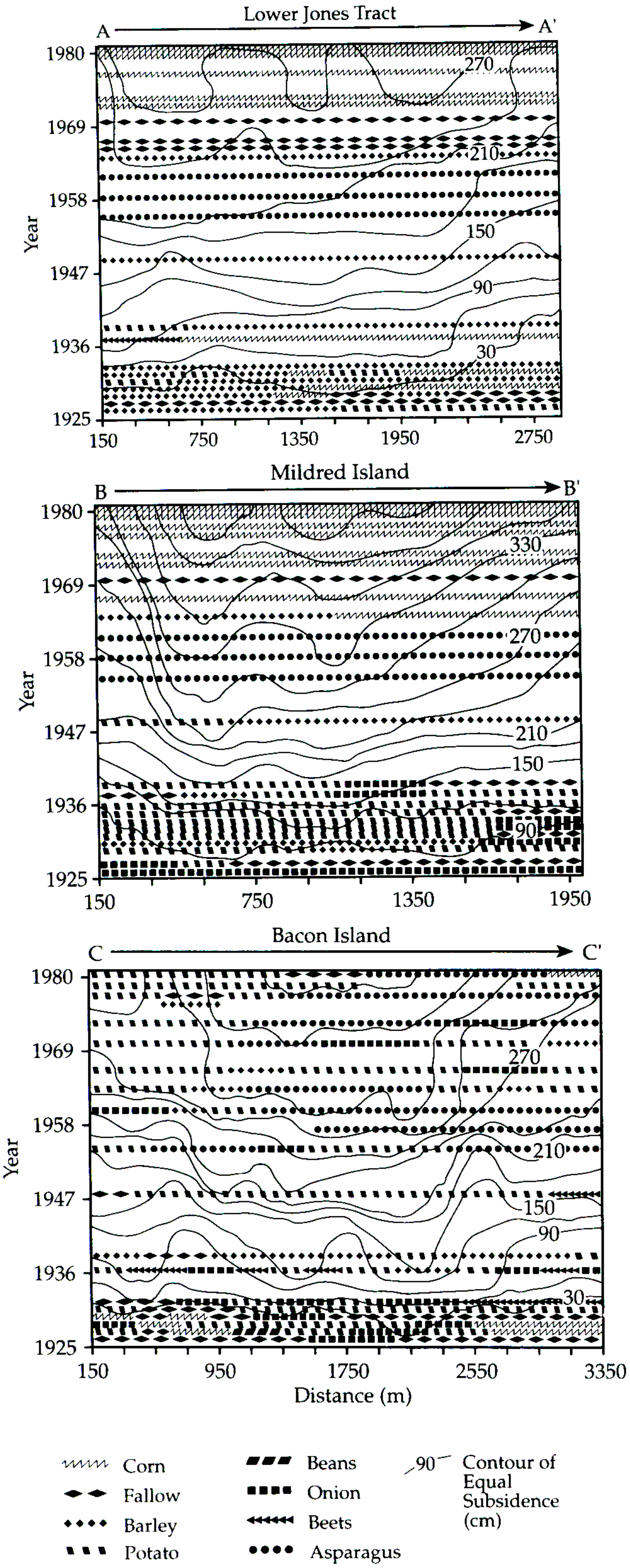


Fig. 6. Spatial variation of subsidence and land-use histories along sections of the transect, 1925 to 1981: (A) Lower Jones Tract, section A-A′ in Fig. 3; (B) Mildred Island, section B-B′; (C) Bacon Island, section C-C′.

ies, the 1925 survey (Weir, 1950) was used as the base elevation. Elevation data from subsequent surveys were subtracted from the base elevation to determine elevation changes since 1925. Figure 6 shows the spatial variations of subsidence and land-use histories from 1925 to 1981 along sections of the transect on Lower Jones Tract, Mildred Island, and Bacon Island. The contours represent the cumulative elevation loss for the years of measurement. Areas with high subsidence rates appear as troughs, and areas with low subsidence rates appear as crests.

While there is significant variability in subsidence rates over time and space, two trends can be identified on all three islands. Contour spacing in Fig. 6 tends to widen with time. This widening is consistent with a declining subsidence rate. The one notable exception occurs between 1938 and 1948 where the contours, particularly in the center of the island, are clustered, implying an increased rate of subsidence during this time. Data regarding land use are not available, as the transect was not surveyed between 1938 and 1948. However, Thompson (1957) observed that sugar beet (*Beta vulgaris* L. ssp. *vulgaris*) and potato (*Solanum tuberosum* L.) were the predominant crops grown in the Delta during World War II (1939–1945) due to the wartime demand for these products. Fields with organically rich soils to be planted to these crops were often burned to increase the ash content and control weeds (Cosby, 1941). Controlled burning was apparently a common practice in the Delta throughout the war years (Thompson, 1957). When organic soil is burned, as much as the top 8 cm of soil can burn (Weir, 1950). The increased subsidence rates measured on Mildred Island and Lower Jones Tract between 1938 and 1948 may be the result of burning. The rates of subsidence during this time period are generally >50% greater than subsidence rates the decade following. If burning is the sole cause of the change, then it is responsible for >1 cm of subsidence per year during this time period.

A historically persistent trough, indicating an area of increased subsidence, occurs toward the center of the transect along both Mildred and Bacon Islands. On Mildred Island, the subsidence trend cannot be correlated with a particular crop type: for any given year, crop type along the transect was virtually uniform. Also, there was no apparent relation between crop type and subsidence for the Bacon Island data. With the possible exception of burning, cultivation and cropping practices do not seem to affect subsidence rates on these three islands. Presumably, spatial trends in subsidence on these islands, similar to Sherman Island, are due to primarily to trends in organic content of the soil.

CONCLUSIONS

Historical measurements of spatially variable subsidence in the Sacramento–San Joaquin Delta were assessed in relation to varying land use and the organic matter contents of the soil. The results of this assessment indicate that: (i) spatially variable subsidence is correlated with organic matter content of the soil, which in turn is related to the depositional and drainage history of the islands; and (ii) different cropping practices do not seem to affect subsidence rates.

These results have significant implications for land use management in areas with extensive Histosols. Although Histosols are valuable for agriculture, their use, especially in coastal regions, can be expected to have a significant environmental impact. It would require the maintenance of a high water table in critical areas with soils of extremely high organic content. In some areas, these land use restrictions may severely limit the viability of agricultural use of Histosols. Extensive acreage may have to be converted to wetland status.

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