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Historic, Recent, and Future Subsidence, Sacramento-San Joaquin Delta, California, USA

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ABSTRACT

To estimate and understand recent subsidence, we collected elevation and soils data on Bacon and Sherman islands in 2006 at locations of previous elevation measurements. Measured subsidence rates on Sherman Island from 1988 to 2006 averaged 1.23 cm year^{-1} (0.5 in yr^{-1}) and ranged from 0.7 to 1.7 cm year^{-1} (0.3 to 0.7 in yr^{-1}). Subsidence rates on Bacon Island from 1978 to 2006 averaged 2.2 cm year^{-1} (0.9 in yr^{-1}) and ranged from 1.5 to 3.7 cm year^{-1} (0.6 to 1.5 in yr^{-1}). Changing land-management practices and decreasing soil organic matter content have resulted in decreasing subsidence rates. On Sherman Island, rates from 1988 to 2006 were about 35% of 1910 to 1988 rates. For Bacon Island, rates from 1978 to 2006 were about 40% less than the 1926–1958 rates. To help understand causes and estimate future subsidence, we developed a subsidence model, SUBCALC, that simulates oxidation and carbon losses, consolidation, wind erosion, and burning and changing soil organic matter content. SUBCALC results agreed well with measured land-surface elevation changes. We predicted elevation decreases from 2007 to 2050 will range from a few cm to over 1.3 m (4.3 ft). The largest elevation declines will occur in the central Sacramento–San Joaquin Delta. From 2007 to 2050, the most probable estimated increase in volume below sea level is 346,956,000 million m^3 (281,300 ac-ft). Consequences of this continuing subsidence include increased drainage loads of water quality constituents of concern, seepage onto islands, and decreased arability.

INTRODUCTION

Subsidence of organic and highly organic mineral soils in the Sacramento–San Joaquin Delta is a primary landscape altering process that threatens delta infrastructure and water supply for over 23 million Californians. To assess risks of levee failure and flooding, it is important to assess present-day and future subsidence. Drainage and cultivation of delta soils since 1850 resulted in subsidence on over 60 islands from one to over eight m (3.3 to 26.2 ft)

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below sea level (Thompson 1957). A levee network protects the islands from flooding.

By reducing the landmass and resistance to hydraulic pressure from adjacent channels, subsidence has contributed to levee failure and island inundation. From 1930 to the early 1980s, over 50 delta islands or tracts flooded due primarily to levee foundation instability (Prokopovitch 1985). Island flooding can cause eastward movement of saline water into the delta during flooding and cause water quality degradation. For example, flooding of Andrus and Brannan islands in June 1972 resulted in water-quality deterioration in the delta that temporarily prevented exports (Cook and Coleman 1973). Subsidence and levee failure also cause local infrastructural damage, which historically has cost hundreds of millions of dollars (Prokopovitch 1985).

Subsidence necessitates deepening of drainage ditches for the maintenance of an aerated crop root zone. Subsidence coupled with sea level rise will increase drainage volumes and loads of dissolved organic carbon and other constituents of concern from delta islands due to the increased hydraulic gradient from delta channels to islands.

The primary cause of delta subsidence is the oxidation of organic or peat deposits, which formed from decaying wetland plants (Atwater 1982; Shlemon and Begg 1975; Drexler and others 2009). During the 6,000 to 7,000 years prior to the 1850s, about five billion cubic meters (4,100,000 ac-ft) of tidal marsh sediment accumulated in the delta (Mount and Twiss 2005). During the last 150 years, half of this volume disappeared and created an accommodation space of over two billion cubic meters (1,600,000 ac-ft) below sea level that can be filled by flood waters (Mount and Twiss 2005).

Soil type and organic matter content vary substantially (Figure 1). Highly organic mineral surface soils generally predominate in the western and northern delta and true surface organic soils, or histosols as defined by Buol and others (1973), predominate in the central, eastern and southern delta. McElhinney (1992), Tugel (1993) and Welch (1977) described the delta soils and Figure 1 is based on their data. The lowest organic matter content soils generally predominate in areas drained prior to 1880 near the Sacramento River.

Table 1 summarizes relevant soils and reclamation information for the delta. In the western and northern delta where highly organic mineral soils predominate, islands were initially drained or reclaimed during the latter half of the 19th century. In contrast, central and eastern delta islands, where true histosols

Table 1 Summary of reclamation history and soil characteristics

| Reclamation Period (Thompson 1957)	Areas and Representative Islands	Predominant Soil Series (McElhinney 1992; Tugel 1993; Cosby 1941; Welch 1977)
1868–1879	Western and northwestern delta: Sherman, Brannan–Andrus, Grand, near Sacramento River.	Highly organic mineral soils (Gazwell, Egbert, Roberts series). Cosby (1941) described the Egbert and Roberts soils as the most altered peats.
1868–1879	Southeastern delta; Roberts Island	Roberts series
1880–1899	Bouldin, Ryer, Tyler, Staten, New Hope, Rindge, Wright–Elmwood, Lower and Upper Jones, Union, Fabian, Bethel, Jersey, Bradford, Twitchell.	Histosols (medisaprists), with medium to high organic matter content; primarily Rindge series. (Cosby's 1941 Staten series which represented an intermediate stage of peat alteration.)
1900–1921	Central and eastern delta (Webb, Mandeville, Bacon, McDonald, Bishop, Venice, Empire, King)	Histosols (medisaprists and medihemists) with generally high soil organic matter content; Rindge, Kingile, Webile, Shinkee, and Shima soil series. (Cosby's Staten and Venice series. The Venice series was closest to the unaltered virgin Correa peat.)
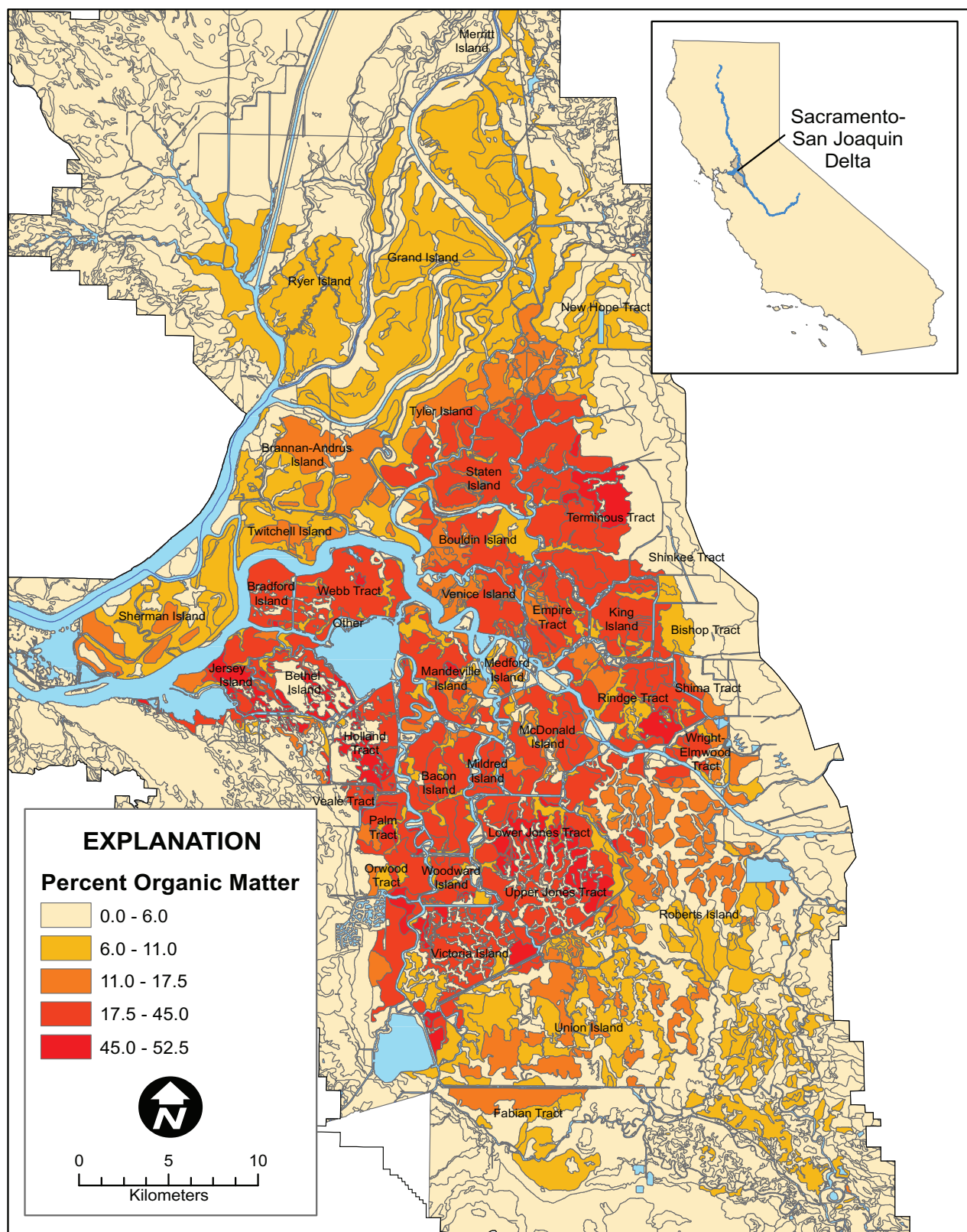
Figure 1 Distribution of percent soil organic matter in the Sacramento–San Joaquin Delta

predominate, were reclaimed during the late 19th century or early 20th century. Prior to reclamation, islands near the Sacramento River were subject to greater fluvial deposition relative to the more quiescent environment in the central and eastern delta.

There is little information about how land-surface elevations have changed during the past 20 to 30 years. The most recently published rates (Deverel and others 1998; Deverel and Rojstaczer 1996; Rojstaczer and Deverel 1995) ranged from 0.6 to 4 cm year^{-1} (0.2 to 1.6 in yr^{-1}). A U.S. Geological Survey operated extensometer for a single location on Twitchell Island showed recent subsidence rates of about 1.3 cm year^{-1} (0.5 in yr^{-1}) since 1994 (Gail Wheeler, U.S. Geological Survey, pers. comm., 2005).

Subsidence rates on Sherman Island varied with soil organic matter content (Rojstaczer and Deverel 1995). Historic subsidence rates for Bacon and Mildred islands and Lower Jones Tract (Deverel and others 1998) were substantially higher than those on Sherman Island due to oxidation of higher organic matter soils. Delta surface soils range in soil organic matter content from less than 5% to over 50% (Figure 1). Soil organic matter content generally increases with depth.

Reported causes of delta subsidence include aerobic microbial oxidation of soil organic matter, anaerobic decomposition, consolidation, shrinkage, wind erosion, gas, water and oil withdrawal, and dissolution of soil organic matter (Prokopovitch 1985, DWR 1980; Weir 1950; Rojstaczer and others 1991; Deverel and Rojstaczer 1996). The relative importance of different causes of delta subsidence has not been quantified but work in other locations indicates that microbial oxidation and consolidation and shrinkage due to dewatering are the primary causes. Stephens and others (1984) reported that oxidation accounted for 53% of historical subsidence in organic soils in the Florida Everglades. Researchers in the everglades demonstrated the correlation of subsidence and CO_2 production (Stephens and Stewart 1976), soil temperature and moisture (Knipling and others 1970; Volk 1973) and microbial activity (Tate 1979, 1980a, 1980b). Schorthorst (1977) reported that compaction, shrinkage, and microbial oxidation caused 28%, 20%,

and 52% of subsidence in the Netherlands, respectively.

Deverel and Rojstaczer (1996) reported that present-day subsidence of delta organic soils is caused primarily by microbial oxidation of organic carbon. Little has been documented about consolidation, a secondary cause of organic soil subsidence. Water in organic soils is held in three phases; intercellular, interparticle water in micropores, and bound or absorbed. Consolidation expulses pore water and particles rearrange (Hobbs 1986). As farmers deepened drainage ditches to compensate for land-surface elevation loss due to oxidation, wind erosion and burning, delta organic soils consolidated due to dewatering. Drexler and others (2009) presented evidence for consolidation below the upper oxidized layer on farmed subsided islands.

The objectives of this paper are to describe rates and causes of historic and recent subsidence and estimate future subsidence. We collected and analyzed elevation and soils data to estimate recent subsidence rates and factors affecting rates. Using data collected during this study and by Rojstaczer and others (1991), Rojstaczer and Deverel (1995), Deverel and Rojstaczer (1996) and the University of California, we assessed recent and historic causes of and factors affecting subsidence rates. We developed a computer model, SUBCALC, and Geographic Information System (GIS) to simulate subsidence.

METHODS

Elevation Determinations and Soil Sample Collection and Analysis

To assess recent subsidence rates, we determined elevations along the survey route followed by Weir (1950) on Bacon Island which was surveyed in 1978. Elevations were determined relative to benchmark EBMUD 10.88 which has a current NGVD 1929 elevation of 10.85 ft. Weir (1950) used an elevation of 10.88 ft. Rojstaczer and others (1991) compiled elevations at discrete locations along the survey route. We used copies of the original survey notes and maps and data complied by Rojstaczer and others (1991) to locate the route and specific locations for elevation determinations on Bacon Island. Rojstaczer and oth-

ers (1991) reported that misclosure for the Weir surveys ranged from 0.01 to 0.13 m (0.4 to 5 in) and the average misclosure was 0.07 m (2.76 in).

Kjeldsen, Sinnock & Neudeck, Inc. (KSN) of Stockton, California, used traditional survey methods and real time kinematic (RTK), static and fast-static Global Positioning System (GPS) measurements to determine elevations and horizontal coordinates at 51 locations (Figure 2). Appendix A provides more detail. In 1988 on Sherman Island, Rojstaczer and others (1991) determined soil loss at power pole foundations constructed in 1910. At thirteen power poles, we determined soil loss using methods identical to those described in Rojstaczer and others (1991).

We collected soil samples adjacent to the Sherman Island 1910 power pole foundations and at the temporary benchmarks on Bacon Island (Figure 2) with a 10-cm (4-in) diameter bucket auger. The soil from the 0 to 30 cm (0 to 1 ft) and 30 to 60 cm (1 to 2 ft) depth intervals was mixed in the field and a sub sample was collected in plastic bag and refrigerated. Samples were analyzed for total organic matter content by loss on ignition (Nelson and Sommers 1982).

Analysis of Historical Subsidence Rates and Soils Data in the Sacramento–San Joaquin Delta

Using standard multiple regression analysis, we evaluated data for percent soil organic-matter from McElhinney (1992) and Tugel (1993) and historic elevation changes relative to location and year of reclamation (Thompson 1957) to assess processes affecting subsidence rates.

Simulation of Historic and Recent Subsidence Rates

We developed the computer model, SUBCALC, coded in FORTRAN-90, to integrate data and quantify and predict subsidence rates and causes on four delta islands: Sherman, Mildred, Lower Jones Tract and Bacon (Figure 1). SUBCALC simulates subsidence due to aerobic microbial oxidation of organic carbon, consolidation, wind erosion and burning. We initially simulated land-surface elevation changes on Bacon Island from 1926 to 2006. Next, including adjust-

ments based on the cropping history provided in Rojstaczer and others (1991), we simulated land-surface elevation changes on Mildred Island and Lower Jones Tract from 1926 to 1981. We also simulated land surface elevation changes on Sherman Island from 1988 to 2006 at power pole foundations. Lastly, we used the model with a Geographic Information System (GIS) to predict future land-surface elevation changes throughout the delta to 2050. Appendix B provides model details and assumptions.

SUBCALC simulates microbial oxidation using Michaelis–Menton kinetics. Soil organic carbon limits soil organic matter oxidation (Browder and Volk 1978). Consolidation of organic deposits results from increased drainage-ditch depth which causes dewatering and reduces interstitial water pressure (and therefore buoyancy) thus transferring load to the soil skeleton. To estimate the consolidation of subsurface deposits, we assumed compaction processes similar to dewatering and irreversible consolidation of a vertical soil column as described by Terzaghi (1925). The use of Terzaghi's effective stress principle is generally restricted by assumptions of Newtonian behavior of the liquid phase. We recognize that water in organic soil does not strictly follow Newtonian mechanical principles, especially during large changes in stress. However, we assumed that for a small increment of annual stress change, dewatering would generally follow Newtonian behavior. SUBCALC simulates this process using a linear equation relating compaction to the change in hydraulic head based on data from the Twitchell Island extensometer (see Appendix B).

Easterly spring winds caused erosion of organic soils primarily from bare asparagus fields (Schultz and Carlton 1959; Schultz and others 1963). Carlton and Schultz (1966) estimated 1.44 cm year^{-1} of wind erosion on Terminous Tract from 1927 to 1957. Weir (1950) and Cosby (1941) stated that farmers burned peat soils to control weeds and diseases once every five to ten years and 7.6 to 12.7 cm (3 to 5 in) of peat disappeared during a single burning. Farmers burned more frequently during World War II (Weir 1950; Rojstaczer and others 1991). SUBCALC uses data described in Carlton and Schultz (1966), Weir (1950)
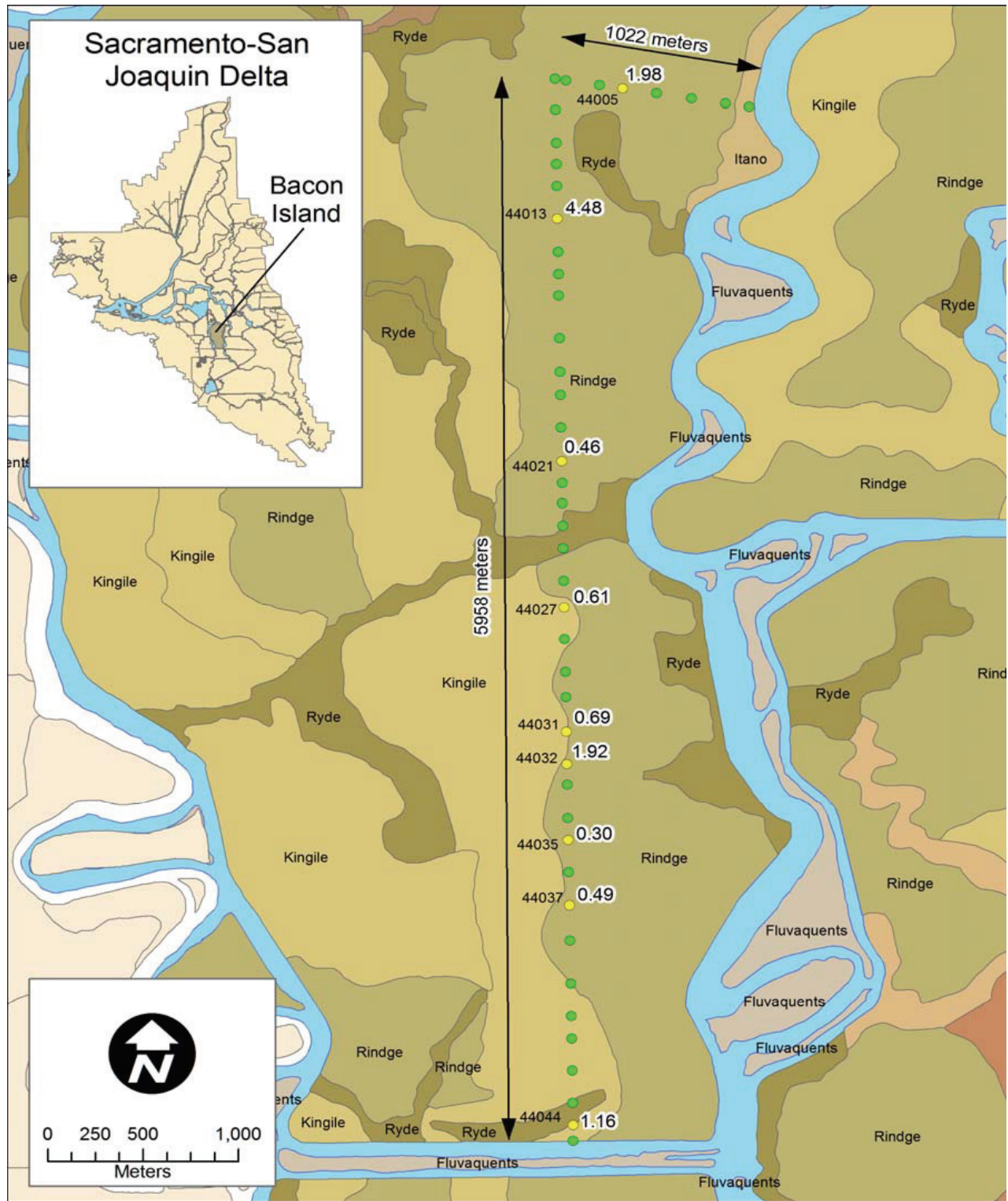
Figure 2 Locations of elevation determinations and soil sampling and depth to bottom of peat on Bacon Island. Numbers to left of point represent location identifier and number to the right is depth to bottom of peat. Labels on different colored polygons are soil series.

and Rojstaczer and others (1991) to calculate the effects of wind erosion and burning. Appendix B provides more detail.

Land-surface Elevations and Estimation of Peat Thickness

Estimates of peat thickness are needed for estimating future subsidence. We estimated peat thickness by subtracting the elevation of the bottom of the peat from land surface elevations. During simulations of future subsidence, land surface elevation was adjusted yearly based on the subsidence calculations. Initial land surface elevations for future subsidence estimates were based on LIDAR (Light Detection and Ranging) data collected by the California Department of Water Resources in January and February 2007. A 27-m (88.7-ft) square grid of peat bottom elevation values was calculated from Atwater's (1982) data by determining the semivariogram and kriging (David 1977) using ArcGIS Geostatistical Analyst software. The Atwater (1982) data included over 1,100 borings. We subtracted the peat bottom elevation from the LIDAR land surface elevation grid in ArcGIS Spatial Analyst software to create a peat thickness grid and map.

Future Subsidence Rates

We estimated spatially variable future subsidence rates to 2050 by using SUBCALC and ArcGIS Spatial Analyst. We assumed that oxidation and consolidation are the only present-day and future causes of subsidence. In yearly intervals beginning in 1990, we assigned subsidence rates to each soil series based on the soil organic matter content provided in Tugel (1993), McElhinney (1992), and Welch (1977).

Soil temperatures will likely increase in the future. For estimating the effects of future temperature changes on subsidence, we assumed that shallow soil temperatures will change proportional to increasing atmospheric temperatures. Probability distributions of future air temperature changes were provided by Dr. Phil Duffy (Lawrence Berkeley Laboratory, pers. comm., 2006). These were based on probabilistic projections of changes in seasonal-mean near-surface air temperatures obtained from the results from 13 independent climate models and three greenhouse

gas emissions scenarios. SUBCALC uses the soil-temperature-organic matter oxidation relation in Deverel and Rojstaczer (1996) to calculate temperature effects on future subsidence.

For future subsidence calculations, we assume that: (1) land use will generally not change; (2) there will be zero subsidence in rice-growing areas; (3) for specific pasture areas, as determined from Department of Water Resources land use maps for Sherman, Jersey and Bradford islands, subsidence rates will be lower due to observed shallower water tables (Stephens and others 1984) and; (4) the subsidence rate is zero where or when the soil organic matter content is less than or equal to 2%. We also assumed subsidence due to gas withdrawal in the western delta based on Rojstaczer and others (1991).

Estimates for future subsidence are uncertain due to (1) spatially variable soil organic matter content, (2) spatial variability in factors affecting oxidative subsidence and consolidation (3) our inability to fully quantify processes, and (4) survey measurement error. We attempted to estimate uncertainty by (1) analyzing the uncertainty of the individual SUBCALC model components and (2) comparing model results with measured subsidence at individual locations on Bacon and Sherman islands.

RESULTS

Estimation of Peat Thickness

Figure 3 shows the estimated peat thickness. The thickest peat resides in the western and northwestern delta where thicknesses range from less than one meter (3.3 ft) on northern Grand Island to over seven meters (23 ft) on Sherman Island. Three to over seven meters of peat remains on Ryer, southern Grand, western Brannan, and Twitchell islands. For most of the central, eastern and southern delta, less than one to two meters of peat remains.

Recent and Historic Subsidence Rates

Delta-wide Relation of Historical Subsidence Rates and Soil Organic Matter Content

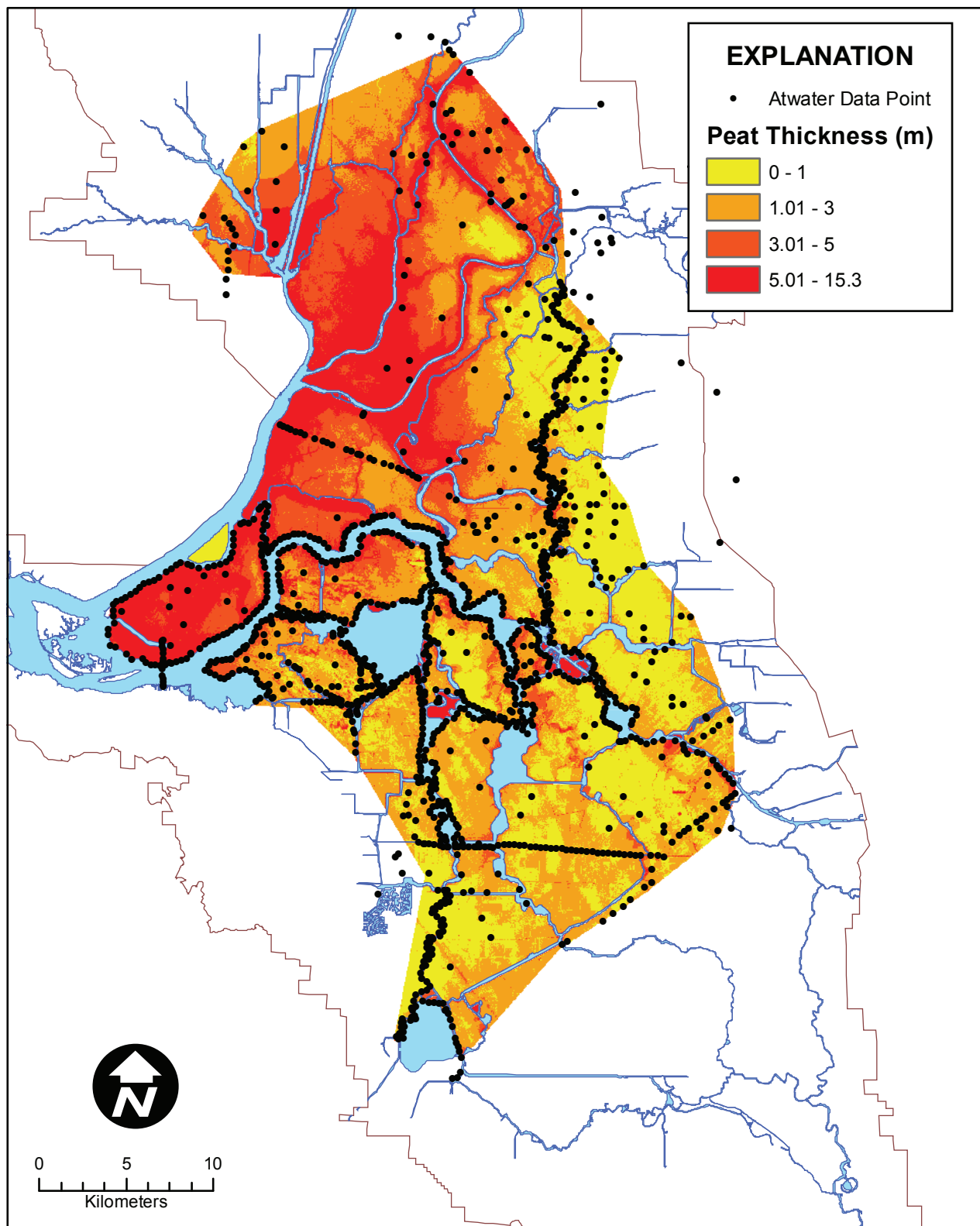For the entire delta, we evaluated the relation of soil organic matter content and subsidence rates from

Figure 3 Estimated peat thickness

about 1906 to 2007. We used digitized U.S. Geological Survey topographic maps for the circa 1906 elevations and we used LIDAR data for the 2007 elevations. The difference between the two elevations divided by the intervening time equals the historic subsidence rate. For 2,570 points the median subsidence rate was 2.6 cm yr^{-1} (1 in yr^{-1}) and the inner quartile range was 1.6 to 3.9 cm yr^{-1} (0.6 to 1.5 in yr^{-1}).

We obtained soil organic matter content from Tugel (1993), McElhinney (1992), and Welch (1977) (Figure 1). The relation of subsidence rates to fraction organic matter was statistically significant (alpha < 0.001) (r^2 = 0.10) and the equation,

$$\text{subsidence rate (cm yr}^{-1}) = 3.68 \times \text{soil organic matter fraction} + 1.85$$

has a similar slope as the equation shown in Figure 5 for data collected on Bacon and Sherman islands. Multiple regression analysis using reclamation data improved the explanation of the variance. The equation,

$$\text{rate (cm yr}^{-1}) = -101 + 2.64 \times \text{soil organic matter fraction} + 0.0545 \times \text{reclamation year,}$$

explained 25% of the variance in subsidence rates and was statistically significant at alpha = 0.001.

Reclamation year varied regionally (Table 1). In general, western and northern islands were reclaimed during the mid to late 19th century. Central and eastern delta islands were reclaimed in the late 19th and early 20th centuries. Soil organic matter percent is a key source of uncertainty in the regression analysis. Tugel (1993) and McElhinney (1992) reported a range in soil organic matter percentages for the soil series, which is not represented in the regression analysis as we used the midpoint of the reported range.

Bacon Island, Mildred Island, and Lower Jones Tract

Subsidence rates from 1978 to 2006 on Bacon Island (Figure 2) varied from 1.5 to 3.8 cm yr^{-1} (0.6 to 1.5 in

yr^{-1}). The average rate was 2.2 cm yr^{-1} (0.87 in yr^{-1}). Subsidence rates increased along the Bacon Island transect from south to north (Figure 4) and the trend is statistically significant at alpha = 0.05 (r^2 = 0.24). At the southern end of the transect (point 44044), the rate was 1.2 cm yr^{-1} (0.47 in yr^{-1}). Near the middle to northern end of the transect, rates were over 3 cm yr^{-1} (1.2 in yr^{-1}). For the west to east transect (data not shown), rates were lowest for the two points closest to the levee. These points are at the edge of the mapped Rindge organic soil and in the Itano highly organic mineral soil.

Soil organic matter percentages ranged from 48% in the north to 11% in the south (point 44043). Peat thickness also increased towards the center of the island and varied from about 4.5 m (14.8 ft) at the northern end of the transect to about 1.2 m (3.9 ft) near the levee (Figure 2). For the west-east transect, organic matter content was higher ranging from 52% to 62% and there was no discernible spatial trend in the data. Figure 5 shows the significant (alpha = 0.05) correlation (r^2 = 0.56) of soil average organic matter fraction in the upper 60 cm (2 ft) of soil to subsidence rates. The soil organic matter percent varied from 14% to 61%.

Figure 6 shows the average measured elevation change for Bacon Island from 1926 to 2006 along the route shown in Figure 2. The average rate was 7.2 cm yr^{-1} (2.8 in yr^{-1}) from 1926 to 1958. From 1958 to 2006 the rate was 2.9 cm yr^{-1} (1.1 in yr^{-1}), 40% less
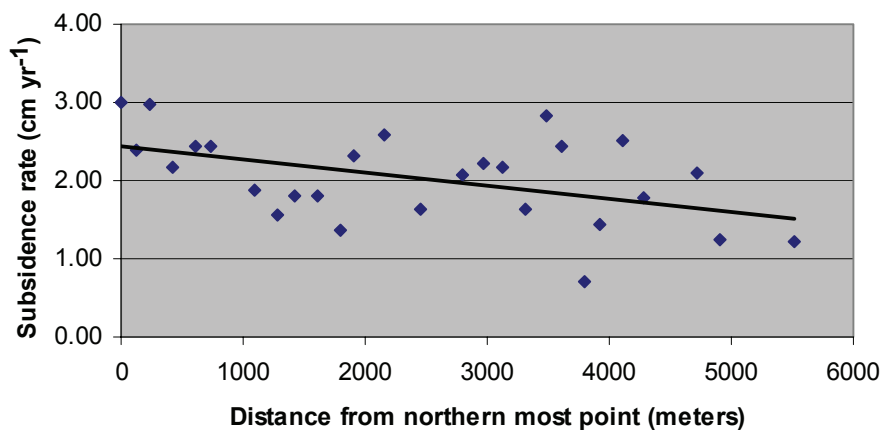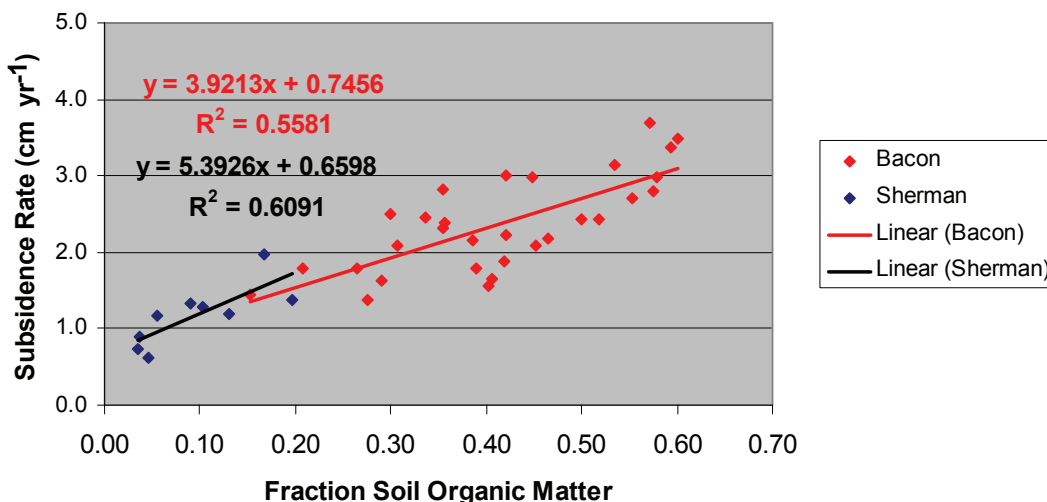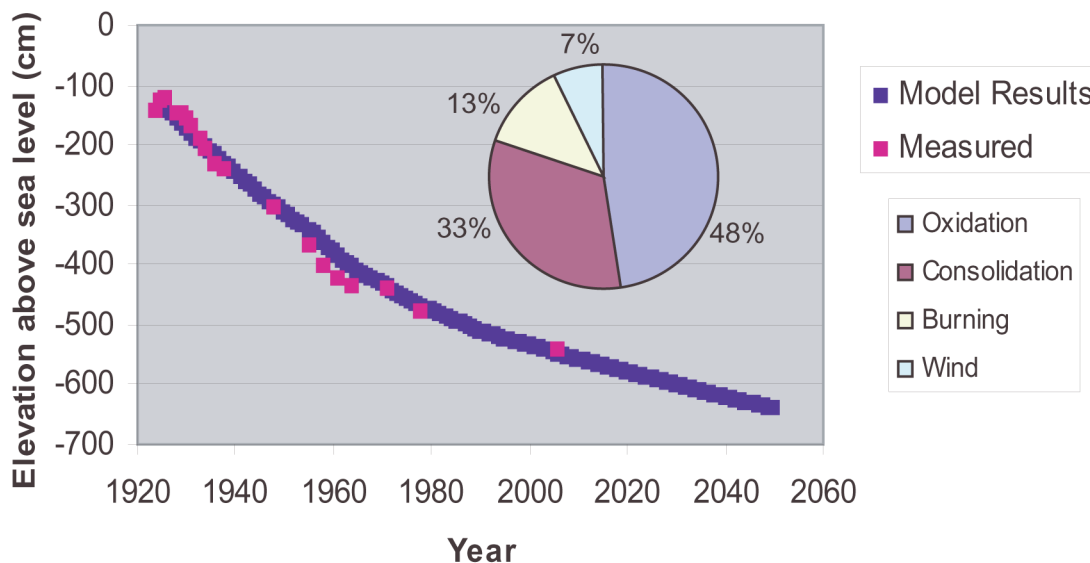
Figure 4 Variation in subsidence rates along the north south transect on Bacon Island shown in Figure 2

Figure 5 Relation of subsidence rates to soil organic matter content for Bacon Island organic soils and Sherman Island highly organic mineral soils


Figure 6 Average measured and model-estimated elevation change on Bacon Island. Pie chart shows the model-estimated causes of subsidence.

than from 1926 to 1958. The 1978–2006 rate was 30% of the 1926–1958 rate.

We used SUBCALC (see Appendix B), to simulate elevation changes on Bacon Island from 1926 to 2006 and predict elevation changes to 2050 (Figure 6). Model results agree well with the measured values. Figure 7 shows decreasing subsidence rates due to

decreasing soil organic matter content (Figure 8) and changing land-management practices. The stair-step appearance in Figure 7 is due to simulated changes in wind erosion and burning. During 1941 to 1945, higher burning rates (see Rojstaczer and others 1991) caused higher subsidence rates. During the late 1950s and early 1960s, wind erosion and burning resulted in higher rates. SUBCALC did not simulate wind ero-
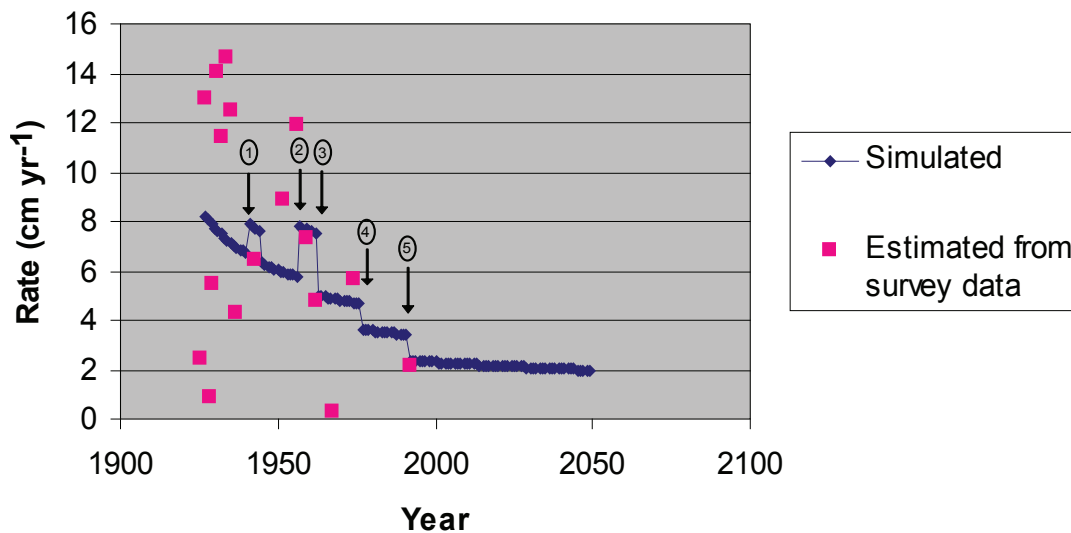
Figure 7 Temporal changes in subsidence rates. Magenta points represent rates estimated from elevation measurements. Circled numbers indicate the following changes in subsidence rates:
1. Increased burning during World War II
2. Wind erosion begins in 1955 with start of aparagus cultivation
3. Burning stopped
4. Rate of wind erosion declined
5. Wind erosion ended (asparagus production ended)

sion before 1954 due to lack of asparagus cultivation. SUBCALC simulated no wind erosion after 1993 when asparagus production stopped. Lower wind erosion rates (0.7 cm yr^{-1}) were used after 1971.

Figure 7 shows an exponential decline but considerable variability in calculated average subsidence rates from measured elevations. These results point to uncertainty in subsidence measurements. During the 1920s and 1930s, Weir and colleagues (Weir 1950) measured elevations frequently. Elevations were affected by tillage and groundwater levels. Deverel and Rojstaczer (1996) showed elastic subsidence at extensometers on three delta islands due to groundwater level fluctuations. Larger elastic land-surface elevation changes would be expected with higher organic matter contents than measured by Deverel and Rojstaczer (1996).

Figure 8 shows the model-estimated decline in soil organic matter fraction of the upper 90 cm (3 ft) which varied from an estimated 0.70 (calibrated value) in 1926 to 0.39 (the average of the data shown in

Figure 5) in 2006. By 2050, we estimated that the average soil organic matter fraction will decrease to about 31%. Figure 8 shows the estimated annual oxidative soil carbon loss (burning is not included in Figure 8) from 1926 to 2050. Temporal carbon-flux changes follow the soil organic matter fraction decline. Values ranged from a high of 0.42 g cm^{-2} yr^{-1} in 1926 to 0.12 g cm^{-2} yr^{-1} in 2050. In 2006, we estimated that 0.15 g cm^{-2} yr^{-1} (15 metric tons ha^{-1} yr^{-1} or 6.7 tons acre^{-1}) were lost. The total estimated carbon lost from 1926 to 2006 was 24 g cm^{-2} or 2,400 metric tons carbon per hectare (1,070 tons A^{-1}).

Figure 9 shows causes of Bacon Island subsidence at 10-year intervals. In the 1920s and 1930s we estimated that oxidation and consolidation contributed about 45% and 34%, respectively. Burning contributed about 21%. Burning during World War II accounted for about 32% of the total subsidence and oxidation and consolidation contributed about 35% and 33%, respectively. During the 1960s and 1970s, wind erosion contributed about 29% and consolidation and oxidation accounted for about 32% and
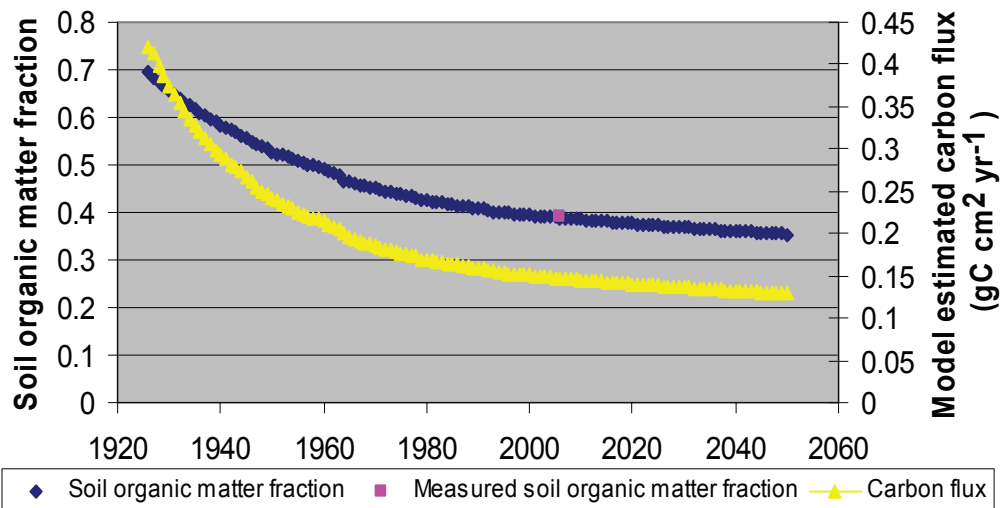
Figure 8 Measured and modeled average soil organic matter content and modeled carbon fluxes for the Bacon Island transect shown in Figure 2.
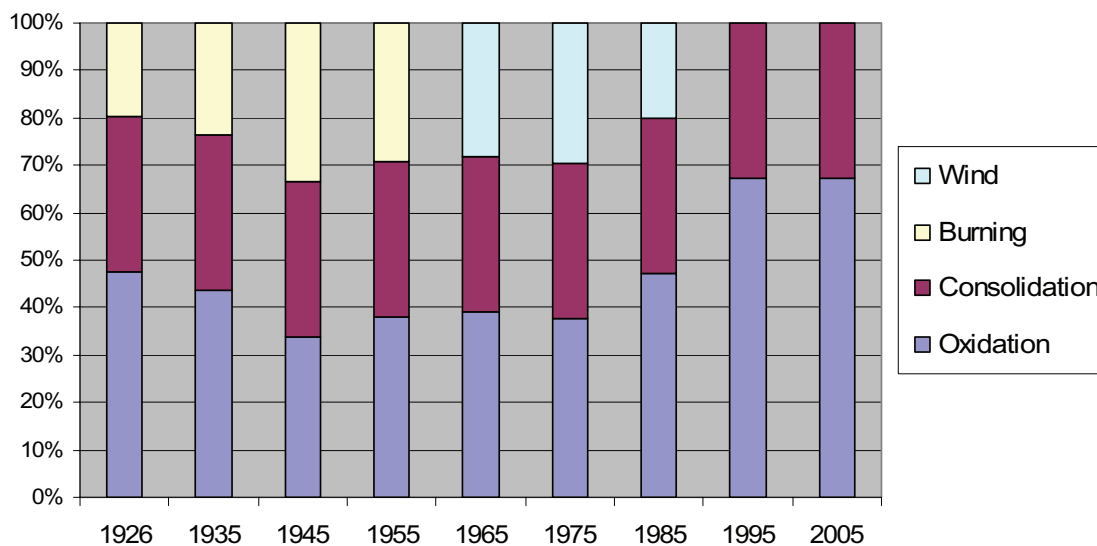
Figure 9 Estimated relative contributions of burning, wind erosion, consolidation and oxidation to total subsidence on Bacon Island, 1926–2005

38%, respectively. Our calculations indicated wind erosion accounted for 20% during the 1980s. During this period, oxidation and consolidation accounted for 48% and 32%, respectively. In 2005, oxidation and consolidation accounted for 68% and 32%, respectively. Overall for Bacon Island from 1926 to 2006, we estimated that oxidation, consolidation, burning and wind erosion accounted for 48%,

33%, 13%, and 7% of the total subsidence of 403 cm (13.2 ft) (Figure 6).

Data collected by Weir and colleagues on Mildred Island and Lower Jones Tract showed similar changes in land-surface elevation declines (Figure 10). To estimate land-surface elevation declines, we used the same methods as Bacon Island except wind ero-

sion differed based on cropping data in Rojstaczer and others (1991). We also calibrated initial organic matter fraction values at 0.81 and 0.61 for Mildred Island and Lower Jones Tract, respectively, to match elevation declines. Model-calculated elevation changes agreed well with measured values. The variation in initial soil organic fraction values is consistent with reclamation year. Lower Jones Tract, Bacon Island, and Mildred Island were reclaimed in 1902, 1915, and 1921, respectively (Weir 1950).

The temporal variability in subsidence causes on Mildred Island was similar to those on Bacon Island as the cropping patterns were similar. However, there was less wind erosion as asparagus was not grown after 1965. From 1963 through 1981, we calculated that oxidation accounted for 62% of the subsidence and consolidation accounted for 38%. From 1955 to 1963 when asparagus was grown, wind erosion accounted for about 19% of the subsidence. We estimated similar temporal variability on Lower Jones Tract. Model results showed that from 1926 to 1981 on Mildred Island, oxidation, consolidation, burning and wind erosion accounted for 44%, 33%, 19% and 4% of the total subsidence of 355 cm (11.6 ft), respectively. For the same period on Lower Jones Tract, oxidation, consolidation, burning and wind erosion accounted for 41%, 34%, 23% and 6% of the total subsidence of 250 cm, (8.2 ft) respectively.

Sherman Island

For Sherman Island, subsidence rates calculated from power-pole-foundation surveys were lower than those
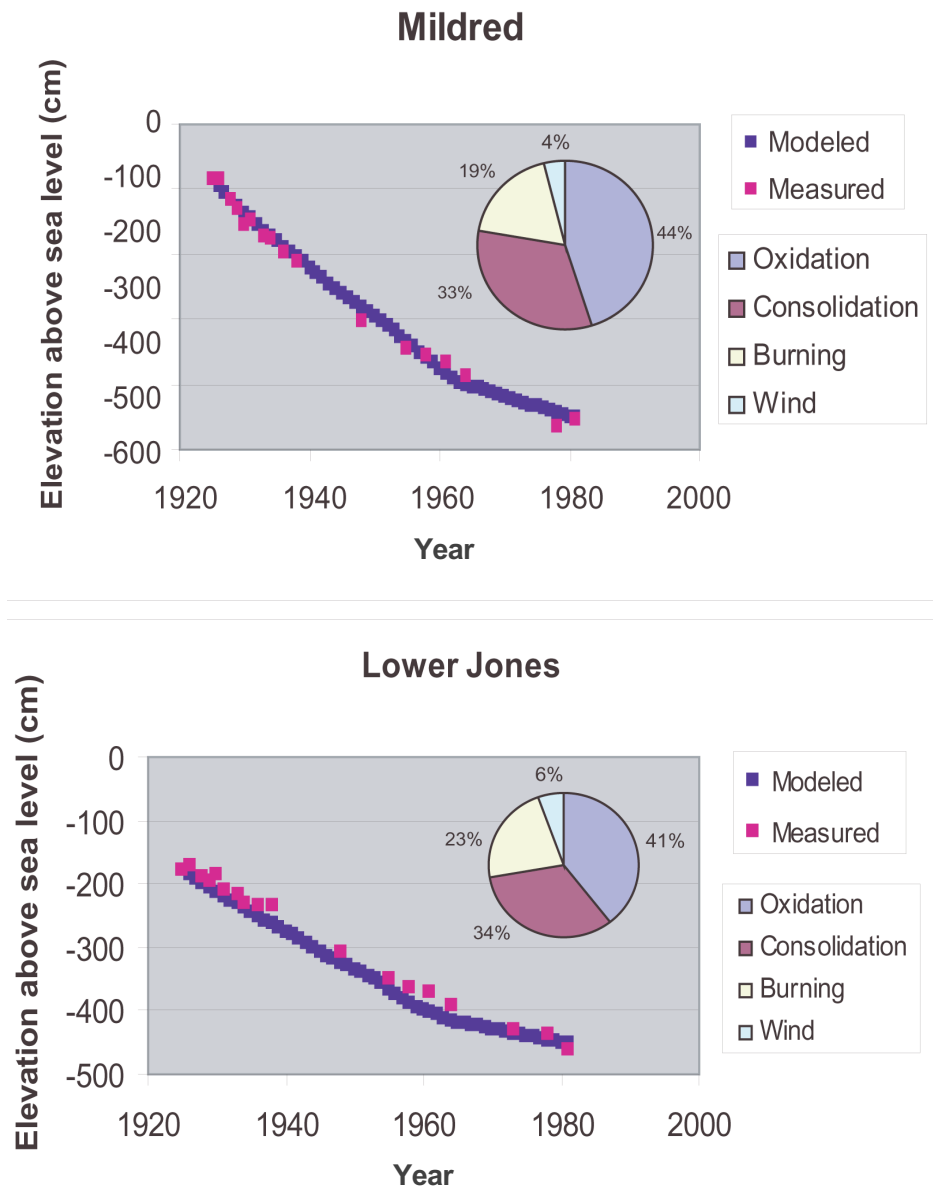
Figure 10 Average measured and model-estimated elevation change on Mildred Island and Lower Jones Tract. Inserted pie graphs show the model-estimated percentages of the causes of sibsidence.

presented in Rojstaczer and others (1991) (Figure 11). The average subsidence rate from 1988 to 2006 was 1.3 cm yr^{-1} (0.5 in yr^{-1}) and ranged from 0.59 to 2.24 cm yr^{-1} (0.2 to 0.9 in yr^{-1}). The average rate from 1910 to 1988 for the same power poles measured by Rojstaczer and others (1991) was 2.01 cm yr^{-1} (0.8 in yr^{-1}) or about 35% greater than the 1988–2006 rate. For three of the 13 power-pole foundations (numbers 274, 281 and 287), calculated soil loss rates were

greater than historical rates reported by Rojstazcer and others (1991). However, the original notes for power pole 274 stated that there were new foundations in 1988 so the original measurements may not have reflected the true 1910–1988 rate. Power pole 287 overlies and is adjacent to a disposal area containing used tires, machinery, etc. The uneven terrain probably affected our ability to effectively measure elevations. For power pole 281, the original 1988 field notes indicated uncertainty in the survey measurements.

Soil organic matter content varied from 0.9% to 19.6%. The soil organic matter percentages reported in Rojstaczer and Deverel (1995) ranged from 4% to 43%. All of the power pole foundations were located on the highly organic mineral soil Gazwell mucky clay except for pole number 280, which was located on the mineral soil Columbia silt loam. Figure 5 shows a significant correlation (alpha = 0.02) between subsidence rates and soil organic matter fraction (r^2 = 0.60). For Figure 5, we removed the power pole foundation data for pole numbers 274, 281 and 287 for reasons stated above. The 1988 notes for power pole 299 indicated measurement error. Corn, alfalfa, and safflower were planted adjacent to the power pole foundations in 2006.

SUBSIDENCE MODELING

Using SUBCALC, we simulated elevation changes at individual measurement locations on Bacon Island from 1978 to 2006 (Figure 2) and the Sherman Island power pole foundations from 1988 to 2006. For Sherman Island, we assumed oxidation and consolidation were the only causes of subsidence. For Bacon Island, the 1978 soil organic matter content value was calibrated to obtain final soil organic matter content values for the upper 60 cm (2 ft) that matched the results of soil analysis conducted during this study. We estimated initial bulk density based the correlation of soil organic matter and bulk density for data presented in Drexler and others (2009) for Bacon Island.

For the Sherman Island simulation, the 1988 soil organic matter content for each power pole was from Rojstaczer and Deverel (1995). The organic matter content of the soil below 60 cm (2 ft) was specified as 7% to 23% organic matter to obtain model results that matched the organic matter contents measured during 2006 sampling. The initial bulk density for 1991 was estimated from the relation of bulk density and organic matter fraction from data presented by Drexler and others (2009). SUBCALC estimated the
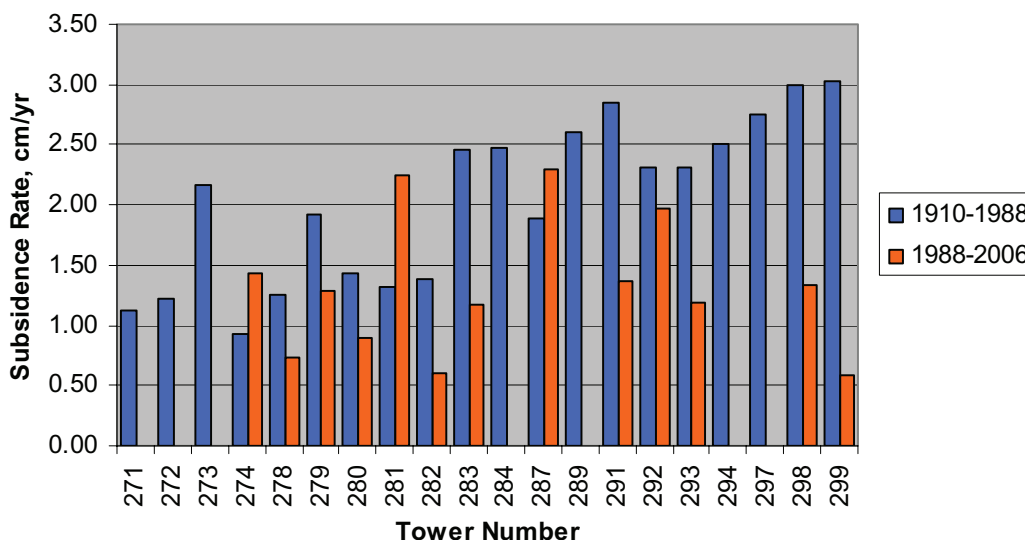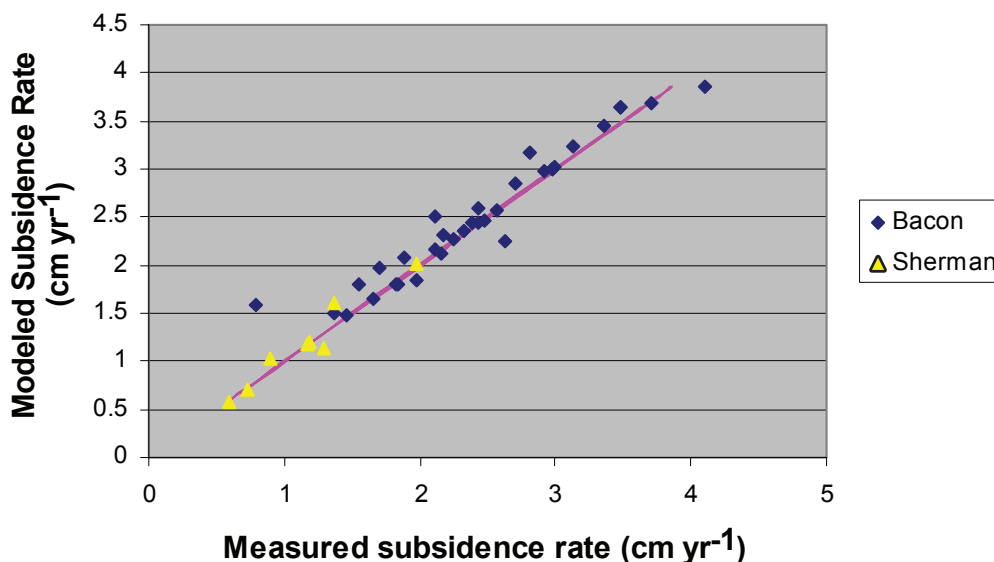

Figure 11 Subsidence rates calculated from elevation measurements against power pole foundations in Sherman Island

14

Figure 12 Comparison of measured and modeled subsidence rates for Sherman Island power pole foundations and measurement locations on Bacon Island shown in Figure 2. Magenta line represents the 1:1 comparison.

average carbon loss in 2006 at 0.016 g cm^{-2} yr^{-1} (values ranged from 0.012 to 0.05 g cm^{-2} yr^{-1}).

Figure 12 shows the comparison of measured and calculated rates for Bacon and Sherman islands. There was generally a good correspondence for all locations; the root mean square error ($[1/n \; \Sigma \; (rate_m - rate_c)^2]^{1/2}$ where rate subscripts m and c refer to measured and calculated values) was 0.2 cm yr^{-1} (0.08 in yr^{-1}). Thus, the model predicted measured subsidence rates within plus or minus 0.20 cm yr^{-1} or about 5.5% of the range of calculated values. For Sherman Island, we predicted subsidence rates within 0.11 cm yr^{-1} (0.04 in yr^{-1}) or 14%. For Bacon Island, we predicted subsidence rates within 0.21 cm yr^{-1} (0.08 in yr^{-1}) or 6%.

For measured and modeled elevations for Mildred Island, Lower Jones Tract, and Bacon Island (Figures 6 and 10) from 1926 to 1981; the root mean square error for predicted elevations for the entire data set was 19.1 cm (7.5 in) or 4.3% of the range of measured elevations. For the individual islands the root mean square error was 15.3 cm (6 in; 3.2%), 16.2 cm (6.4 in; 6.1%) and 19.6 cm (7.7 in; 4.7%) for Mildred Island, Lower Jones Tract, and Bacon Island, respectively.

**Estimated Future Land Surface Elevations and Volume Below Sea Level**

We used SUBCLAC and GIS methods to estimate land surface elevations and volume below sea level for 2050. Table 2 shows the volumes below sea level for 2007 and 2050. The volumes shown in Table 2 were calculated for islands within the peat elevation grid file generated from Atwater (1982) (Figure 3). We assumed a sea level rise for three different scenarios reported by Cayan and others (2006) of 0.06, 0.15, and 0.33 m (0.2, 0.5, and 1.1 ft) by 2050. Our estimates (see uncertainty discussion below) indicate an average increase of about 346,956,000 m^3 (281,300 ac-ft) below sea level (plus or minus about 40 million m^3) by 2050.

Table 2 Estimated volumes below sea level for 2007 and 2050 in cubic meters

Year	Low Estimate	Mean Estimate	High Estimate
2007	---	2,070,189,000	---
2050	2,382,110,000	2,417,145,000	2,466,589,000

Figure 13 shows estimated elevation change in the delta for 2007–2050. The estimated subsidence ranged from a few centimeters to 1.36 m (0 to 4.5 ft). We
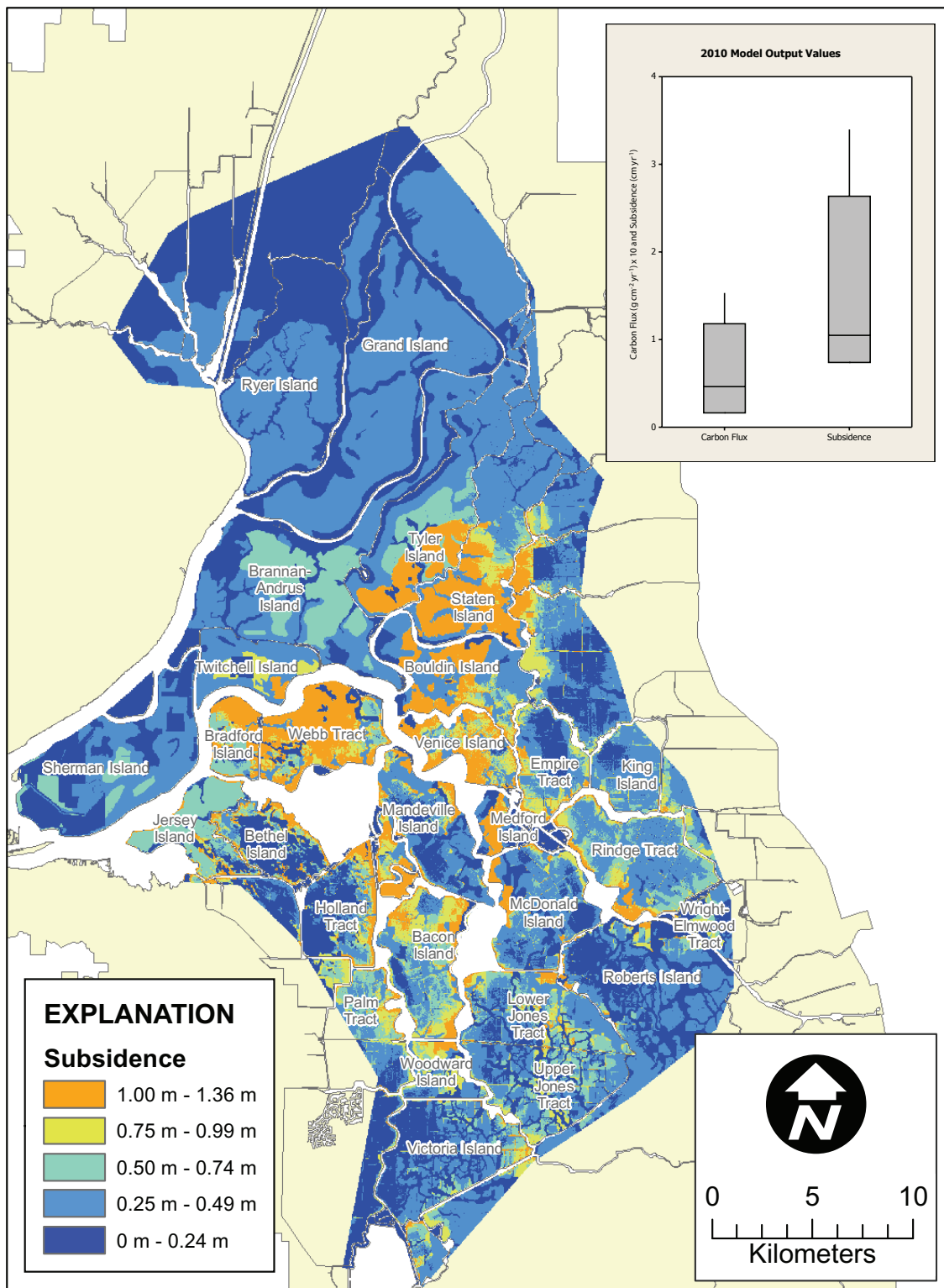
Figure 13 Estimated depth of subsidence from 2007 to 2050. Insert shows box plot of 2010 model-estimated carbon fluxes and subsidence rates. Shaded rectangle is inner quartile range and hoorizontal line in rectangle is the median. The vertical line above the box extends to the 90th percentile.

predicted that as much as 1.36 m (4.5 ft) of subsidence will occur in the central delta by 2050. Less than one meter will occur in the western, northern, and southern delta. In some areas, the peat will completely disappear (for example, Mandeville Island in the central delta). We estimated less subsidence in some areas of the western delta, such as Sherman Island, because of low soil organic matter content and maintenance of a shallow water table in grazing areas. The percent increase in volume below sea level varies by island size.

We estimated that over 65% of the volume increase will be due to subsidence on the largest islands: Bacon, Brannan–Andrus, Grand, Lower and Upper Jones, Mandeville, McDonald, Rindge, Ryer, Sherman, Staten, Terminous, Tyler, Union, Victoria, and Webb. The median model-estimated subsidence rate for 2010 (Figure 13) was 1.0 cm yr^{-1} (0.4 in yr^{-1}) and values ranged from 0.74 to 3.4 cm yr^{-1} (0.3 to 1.3 in yr^{-1}). The median carbon flux was 0.05 g cm^{-2} yr^{-1} and values ranged from 0.016 to 0.15 g cm^{-2} yr^{-1} (Figure 13). The high and low model-estimated median subsidence rates were 0.86 (0.34 in yr^{-1}), (range was 0.7 to 2.6 cm yr^{-1}, 0.03 to 1.0 in yr^{-1}) and 1.2 cm yr^{-1} (0.47 in yr^{-1}) (range was 0.8 to 4.5 cm yr^{-1}, 0.3 to 1.8 in yr^{-1}), respectively.

Uncertainty Analysis of Subsidence Rates and Predictions

Key uncertainty sources for future subsidence estimates include spatial and temporal variability in soil organic matter content, soil temperature, bulk density, unsaturated-zone and peat thickness, land use and model inputs for consolidation and carbon flux equations. Soil organic matter explains much of the variance in subsidence rates and there is some data for the spatial distribution of near surface soil organic matter content (Tugel 1993; McElhinney 1992; Welch 1977; Figure 1). Tugel (1993) and McElhinney (1992) also provided a range of organic matter content values.

Future changes in soil organic matter content will depend on soil temperatures. Initial soil bulk density affects prediction of future subsidence rates. Drexler

and others (2009) provided data that show the relation of bulk density to soil organic matter content.

For estimating future subsidence we assumed that (1) land use will generally not change and (2) the depth of the unsaturated zone will be approximately constant [about 90 to 120 cm (3 to 4 ft)], except for specific pasture areas as determined from Department of Water Resources land use maps. In these areas we adjusted subsidence rates based on observed shallower water tables and information provided in Stephens and others (1984). For example, for identical soil types and temperature regimes, the subsidence rate for a groundwater table at about 30 cm (1 ft) is about 20% of the subsidence rate for a groundwater table at 120 cm (4 ft). In rice-growing areas on Twitchell Island, Bract Tract, and Wright–Elmwood Tract, we set the subsidence rate to zero based on data from Miller and others (2000). We also set the subsidence rate to zero where or when the soil organic matter content was less than or equal to 2%.

To determine uncertainty in estimated future subsidence rates, we varied key model inputs to reflect variance in data used to derive model inputs. Based on the model runs that included variation in parameters described in Appendix B and evaluation of the range in subsidence rates for Bacon Island data, we developed three model input data sets for each soil series that represent the likely range of future subsidence-rate estimates. The key variables influencing rates are fraction soil organic matter, initial bulk density, soil temperature and the dependence of oxidation rates on soil temperature. These variables were varied, within the range discussed in Appendix B, to generate three likely future subsidence rates that approximately represent the inner quartile range for each soil series.

The simulation depth for subsidence is 90 cm (3 ft) and the model simulates soil organic matter changes based on incorporation of organic material below the simulation depth. We estimated the organic matter content of the material below the simulation depth from data presented in Drexler and others (2009). For future subsidence, when the organic matter thickness decreased to less than 90 cm (3 ft), we used the

mean value of the epiclastic sediments below the peat shown in Drexler and others (2009) of 0.10.

DISCUSSION

The peat thickness map (Figure 3) provides insight to organic matter deposition. Shlemon and Begg (1975) proposed eastward spreading peat formation during the early Holocene and hypothesized that peat thickness decreased from east to west. Figure 3 shows that the thickest organic deposits are in the western and northwestern delta. Figure 3 points to eastward and southeastward spreading organic deposition but in contrast to Shlemon and Begg (1975), provides evidence for early northeasterly organic deposition along the Sacramento River.

Regionally and locally, the distribution of soil organic matter content and reclamation history illustrates probable factors and processes affecting the current distribution of subsidence rates. Low organic matter content soils predominate in the western and northwestern delta where lower subsidence rates were measured and calculated. These were generally the first organic deposits reclaimed for agriculture in the mid to late 1800s. Prior to reclamation, those islands near the Sacramento River were subject to greater fluvial mineral deposition relative to the more quiescent environment in the central and eastern delta. Higher organic soils predominate in the central, eastern, and southern delta where higher subsidence rates were measured and calculated. Consistently, our multiple linear regression analysis of subsidence rates from the early 1900s to 2007 showed a statistically significant influence of soil organic matter content and reclamation year.

At the local scale of individual islands, subsidence rates, peat thickness, and soil organic matter content generally increase from the edges to the centers of islands. Rojstaczer and Deverel (1995), Rojstaczer and others (1991), and Deverel and others (2007a) illustrated this for Sherman and Twitchell islands; the Bacon Island data are consistent with this trend. Since most island levees were built on natural levees (Thompson 1957), greater fluvial deposition at island margins probably resulted in greater mineral content relative to the more quiescent island center where

primarily organic accretion occurred. Decreasing peat thickness closer to the levee observed on Bacon Island is also consistent with the geologic cross section shown in Deverel and others (2007a).

Spatially variable subsidence was significantly correlated with soil organic matter content on Sherman and Bacon islands. Microbial oxidation of the delta soil organic matter is substrate limited, so as soil organic matter content decreases, subsidence rates decrease. Consistently, average subsidence rates for Sherman Island (1988 to 2006) and Bacon Island (1978 to 2006) were 35% to 40% lower than measured rates from 1926 to 1958 on Bacon Island and 1910 to 1988 on Sherman Island. Volk (1973) and Tate (1980a, 1980b) demonstrated the applicability of substrate (organic matter) limitations on microbial metabolism of peat in the Florida Everglades. Changing land-management practices are also responsible for slowing subsidence rates. Prior to the early 1960s, burning and wind erosion caused soil loss. Burning no longer occurs and there is minimal wind erosion because there is generally vegetative cover during spring.

We used SUBCALC to quantify processes and predict future subsidence. Model results and their agreement with measurements demonstrate that oxidation accounts for the majority of present-day measured subsidence and the remaining portion is the result of consolidation. The application of Michaelis–Menton kinetics using constants from Jersey Island accurately simulated oxidative subsidence. Consistently, Volk (1973) indicated that Michaelis–Menton kinetics appropriately described oxidation of peat soils in the Florida Everglades. Also, Drexler and others (2009) provided evidence for consolidation of unoxidized organic soils below the groundwater table on subsided islands. Our application of soil mechanical compaction theory that is based on local extensometer and groundwater data appears valid for estimating this consolidation, which is the result of dewatering and transference of effective stress from the interstitial water to the soil skeleton.

Oxidation of organic deposits releases CO_2 and other oxidation products, some of which are transported by percolating waters to drainage ditches. Island drain-

age water contributes to elevated DOC and disinfection by-product precursor concentrations in delta channel waters in winter and early spring. Ongoing organic soil oxidation (primarily during spring, summer, and fall) and subsequent DOC leaching by winter precipitation constitute the yearly aqueous carbon loss cycle (Deverel and others 2007a).

Gaseous carbon dioxide fluxes vary with soil organic matter content. For Bacon Island, estimated carbon loss ranged from a high of 0.42 g carbon cm^{-2} yr^{-1} in 1926 to 0.15 g carbon cm^{-2} yr^{-1} (15 metric tons ha^{-1} yr^{-1} or 6.7 tons $acre^{-1}$) in 2006. We estimated similar carbon losses for Lower Jones Tract and Mildred Island. On Sherman Island, where soil organic matter content is substantially lower, we estimated the average carbon loss in 2006 at 0.016 g carbon cm^{-2} yr^{-1} (1.6 metric tons ha^{-1} or 0.7 tons $acre^{-1}$). For the entire delta, the 2010 median model-estimated median carbon flux was 0.05 g cm^{-2} yr^{-1} with values ranging from 0.016 to 0.15 g cm^{-2} yr^{-1} (Figure 13). The high value of 0.15 g cm^{-2} yr^{-1} is identical to the 2006 Bacon Island value for the average organic matter content of 39%. This is consistent with our use of the mid-range soil organic matter content values from McElhinney (1992) and Tugel (1993) to estimate a median depth of subsidence; the soil organic matter content value was about 40%.

The range of values for carbon loss and subsidence shown in Figure 13 included non-zero values for soils having 2% or greater organic matter content. Large areas will experience little or no oxidative carbon loss or subsidence due to lack of soil organic matter. For the low and high model simulations, we used the upper and lower values of the range presented in McElhinney (1992) and Tugel (1993). For the low and high model simulations, median carbon fluxes were 0.03 and 0.06 g cm^{-2} yr^{-1}, respectively. Values ranged from .001 to 0.12 g cm^{-2} yr^{-1} and 0.03 to 0.2 g cm^{-2} yr^{-1} for the low and high model simulations, respectively.

Carbon emission estimates are consistent with values reported by other authors. For comparable organic matter content (46%) but shallower water table depths (25 cm) Volk (1973) reported 0.05 g carbon cm^{-2} yr^{-1} at 15°C. The groundwater table on most delta islands is about 90 to 120 cm (3 to 4 ft) below land surface. For organic matter content soils that ranged from 20 – 30% organic matter, Deverel and Rojstaczer (1996) measured carbon losses *in situ* on Jersey and Sherman islands and Orwood Tract. They used carbon-14 and carbon-13 in gas samples (Rojstaczer and Deverel 1993) to estimate the portion of the carbon flux attributable to peat oxidation. Values ranged from 0.07 to 0.11 g carbon cm^{-2} yr^{-1} (7 to 11 metric tons ha^{-1} or 3.1 to 4.9 tons $acre^{-1}$).

The consequences of continuing subsidence include greater hydraulic gradients onto delta islands and probable increased subsurface drainage loads of DOC, methylmercury and other constituents of concern. For example, Deverel and others (2007b) used groundwater flow and solute transport models to estimate that DOC loads in island drain-water volumes will increase by 15% to 20% on Twitchell Island by 2050. The results of a recently completed three-year Regional Water Quality Control Board funded assessment of methylmercury concentrations and loads on eight delta islands showed a statistically significant correlation of average methylmercury loads and depth of subsidence indicating that continuing subsidence will likely increase methylmercury loads (Heim and others 2009).

Continuing subsidence will make farming more difficult and expensive. For example, as peats disappear, drainage ditches will be excavated in the underlying mineral sediments which can be unstable. Drainage costs will increase due to increasing pumping lifts. Many deeply subsided islands contain areas that are no longer arable due to saturated and unstable soils. This trend will increase with continuing subsidence. Seepage onto islands will increase and decrease levee stability. For example, Deverel and others (2007b) predicted that seepage onto Twitchell Island will increase by 22% to 34% by 2050. Cumulative hydraulic forces on levees will increase with increasing subsidence and sea level rise (Mount and Twiss 2005).

Our results indicate that deep regional subsidence due to gas withdrawal may play a more important role in the western delta as shallow subsidence rates continue to decline. The geometry and geology of the Rio Vista

Gas Field, widely spread and shallow thin Cretaceous and Eocene gas bearing sands and shales, are consistent with inelastic compaction due to depressurization (Martin and Serdengecti 1984). In some areas of the western delta, installation of gas wells has increased substantially during the past decade.

Cesium-137 data (Rojstaczer and others 1991) indicated a maximum regional gas-withdrawal subsidence rate in the western delta of about 0.5 cm yr^{-1} (0.2 in yr^{-1}) from 1963 to 1989. We measured and estimated an average subsidence rate of 1.3 cm yr^{-1} (0.5 in yr^{-1}) on Sherman Island and the lowest rate was 0.59 cm yr^{-1} (0.23 in yr^{-1}). Given the range of values for highly organic mineral soils on Sherman Island and Twitchell Island (about 1.3 cm yr^{-1} (0.5 in yr^{-1}) (Gail Wheeler, U.S. Geological Survey, pers. comm., 2005), this regional deep subsidence is significant in the western delta.

Delta subsidence will continue for several decades until management practices are adopted that stop subsidence or the organic deposits disappear. We estimated that land surface elevations throughout much of the delta will decrease by 2050 and that currently about 27,000 m^3 are lost daily due to subsidence. Our calculations indicate that 54% of the original volume of 4.5 billion m^3 of peat disappeared during the last 160 years. This is consistent with Mount and Twiss (2005) and generally consistent with Drexler and others (2009) who used carbon-14 data from cores at 12 locations to show that 20% to 45% (the average of eight cores from four islands was 32%) of the peat remains on four farmed islands in the western and central delta (Sherman, Webb, Bacon, and Venice).

Accounting for sea level rise and subsidence, we estimated that the volume below sea level will increase by an additional 346,956,000 m^3 (281,300 ac-ft) by 2050. Land uses such as pasture and rice slow or stop subsidence due the small unsaturated zone or flooded conditions. Managed and permanently flooded wetlands will stop and reverse the effects of subsidence (Deverel and others 1998; Miller and others 2000, 2009).

SUMMARY AND CONCLUSIONS

Elevation and soils data on Bacon and Sherman islands in 2006 provided insight about recent subsidence rates and processes affecting subsidence. Our subsidence model SUBCALC simulates oxidation, compaction, wind erosion and burning and estimated temporally and spatially variable past and future subsidence rates. We used SUBCALC and GIS to estimate volumes below sea level. The following summarizes our key conclusions.

Regionally, soil organic matter content and subsidence have been influenced by depositional environment and reclamation year. Spatially variable historic subsidence rates from the early 1900s to 2007 are significantly correlated with year of reclamation and soil organic matter content. Lower soil organic matter is associated with riverine influence. Higher organic matter soils are associated with the more quiescent central delta.

Historically, subsidence resulted from oxidation of soil organic matter, consolidation, burning, and wind erosion. Growers deepened drainage ditches to maintain sufficient unsaturated zone for crop production and this caused consolidation of the subsurface organic materials. As soil organic matter was lost, soil percent organic matter decreased, which in turn lowered subsidence rates.

The average measured subsidence rate on Sherman Island from 1988 to 2006 was 1.25 cm yr^{-1} (0.5 in yr^{-1}) and values ranged from 0.6 to 2.24 cm yr^{-1} (0.2 to 0.9 in yr^{-1}). The average measured subsidence rate on Bacon Island from 1978 to 2006 was 2.2 cm yr^{-1} (0.9 in yr^{-1}) and ranged from 1.5 to 3.7 cm yr^{-1} (0.6 to 1.5 in yr^{-1}). Subsidence rates were significantly correlated with soil organic matter content. Changing land-management practices that eliminated or reduced burning and wind erosion and decreasing soil organic matter content resulted

in decreasing subsidence rates. Sherman Island rates from 1988 to 2006 were about 35% of 1910 to 1988 rates. Bacon Island rates from 1978 to 2006 were about 40% less than the 1926 to 1958 rates.

SUBCALC results agreed well with average measured land-surface elevation changes on Bacon, Mildred, and Sherman islands and Lower Jones Tract. Assuming unchanging land use and considering uncertainty in the distribution of soil organic matter and bulk density and other model input parameters, we represented likely scenarios for increases in volume below sea level and elevation decreases. We predict that delta land surface elevations will decrease from a few centimeters to over 1.3 m (4.3 ft) by 2050. The median model-estimated subsidence rate for 2010 was 1.0 cm yr^{-1} (0.4 in yr^{-1}) and values ranged from 0.74 to 3.4 cm yr^{-1} (0.3 to 1.3 in yr^{-1}). The largest elevation loss of about 1.36 m (4.5 ft) will occur in the central delta. Less elevation loss will occur in the western, northern and southern delta. Sea level rise and subsidence will increase the volume below sea level by about 346,956,000 m^3 (281,300 ac-ft) by 2050.

ACKNOWLEDGEMENTS

REFERENCES

Atwater BF. 1982. Geologic maps of the Sacramento–San Joaquin Delta. U.S. Geological Survey Miscellaneous Field Studies Map MF–1401.

Browder JA, Volk BG. 1978. Systems model of carbon transformations in soil subsidence. Ecological Modeling 5:269–292.

Buol SW, Hole FD, McCracken RJ. 1973. Soil genesis and classification. Ames (IA): The Iowa State University Press.

Carlton AB, Schultz HB. 1966. Annual statements of progress for project 1686, 1955 to 1966, peat land conservation and peat dust abatement. Davis (CA): University of California, College of Agriculture, Agricultural Experiment Station, Department of Soils and Plant Nutrition.

Cayan D, Bromirski P, Hayhoe K, Tyree M, Dettinger M, Flick R. 2006. Projecting future sea level. A report from the California Climate Change Center. CEC–500–2005–202–SF.

Cook J, Coleman D. 1973. Disaster strikes Isleton. Reclamation Era 59:1–9.

Cosby SW. 1941. Soil survey of the Sacramento–San Joaquin Delta Area, California. Bureau of Plant Industry, U.S. Department of Agriculture. p 1–47.

David M. 1977. Geostatistical ore reserve. New York (NY): Elsevier Scientific.

[DWR] California Department of Water Resources. 1980. Subsidence of organic soils in the Sacramento–San Joaquin Delta. Sacramento (CA): Central District, California Dept. of Water Resources.

Deverel SJ, Leighton DA, Finlay MR. 2007a. Processes affecting agricultural drainwater quality and organic carbon loads in California's Sacramento–San Joaquin Delta. San Francisco Estuary and Watershed Science [Internet]. Available from: *http://www.escholarship.org/uc/item/5j76502x*.

Deverel SJ, Leighton DA, Sola–Llonch N. 2007b. Appendix C: Evaluation of island drain flow, seepage, and organic carbon loads, Sacramento–San Joaquin Delta. Results from the Delta Learning Laboratory Project, Objectives 2 and 3. Prepared for California Department of Water Resources and CALFED Bay Delta Authority under DWR Agreement 4600000659 CALFED Project 98–C01, January 26, 2007.

Deverel SJ, Rojstaczer SA. 1996. Subsidence of agricultural lands in the Sacramento–San Joaquin Delta, California: role of aqueous and gaseous carbon fluxes. Water Resources Research 32:2359–2367.

Deverel SJ, Wang B, Rojstaczer SA. 1998. Subsidence in the Sacramento–San Joaquin Delta. In: Borchers JW, editor. Proceedings of the Joseph Poland Subsidence Symposium, Association of Engineering Geologists.

Drexler JZ, de Fontaine CS, Deverel SJ. 2009. The legacy of wetland drainage on the remaining peat in the Sacramento–San Joaquin Delta, California, USA. Wetlands 29:372–386.

Heim WA, Deverel SJ, Stephenson M. 2009. Farmed islands and monomethylmercury in the Sacramento–San Joaquin Delta. Final report submitted to the Central Valley Regional Water Quality Control Board.

Hobbs NB. 1986. Mire morphology and the properties and behaviour of some British and foreign peats. Quarterly Journal of Engineering Geology (London) 19:7–80.

Knipling EB, Schroeder VN, Duncan WO. 1970. CO_2 evolution from Florida organic soils. Proceedings of the Soil and Crop Science Society of Florida 30:320–326.

Martin JC, Serdengecti S. 1984. Subsidence over oil and gas fields. In: Holzer TL, editor. Man-induced land subsidence. Reviews in Engineering Geology, Vol. VI. Boulder (CO): Geological Society of America.

McElhinney MA. 1992. Soil survey of San Joaquin County. U.S. Department of Agriculture, Soil Conservation Service.

Miller RL, Fram MS, Wheeler G, Fujii R. 2008. Subsidence reversal in a re-established wetland in the Sacramento–San Joaquin Delta, California, USA. San Francisco Estuary and Watershed Science [Internet]. Available from: *http://www.escholarship.org/uc/item/5j76502x*.

Miller RL, Hastings L, Fujii R. 2000. Hydrologic treatments affect gaseous carbon loss from organic soils, Twitchell Island, California, October 1995–December 1997. U.S. Geological Survey Water Resources Investigations Report 00–4042.

Mount J, Twiss R. 2005. Subsidence, sea level rise, seismicity in the Sacramento–San Joaquin Delta. San Francisco Estuary and Watershed Science [Internet]. Available from: *http://www.escholarship.org/uc/item/4k44725p*.

Nelson DW, Sommers LE. 1982. Total carbon, organic carbon, and organic matter. In: Page AL, editor. Methods of soil analysis. Part 2, Chemical and microbiological properties. Madison (WI): American Society of Agronomy, Soil Science Society of America.

Prokopovitch NP. 1985. Subsidence of peat in California and Florida. Bulletin of the Association of Engineering Geologists 22:395–420.

Rojstaczer SA, Deverel SJ. 1993. Time dependence in atmospheric carbon inputs from drainage of organic soils. Geophysical Research Letters 20:1383–1386.

Rojstaczer SA, Deverel SJ. 1995. Land subsidence in drained histosols and highly organic mineral soils of California. Soil Science Society of America Journal 59:1162–1167.

Rojstaczer SA, Hamon RE, Deverel SJ, Massey CA. 1991. Evaluation of selected data to assess the causes of subsidence in the Sacramento–San Joaquin Delta, California. U.S. Geological Survey Open File Report 91–193.

Schorthorst CJ. 1977. Subsidence of low moor pear soil in the western Netherlands. Wageningen (Netherlands): Institute of Land and Water Management Research. Technical Bulletin 102 p 265–291.

Schultz HB, Carlton AB. 1959. Field windbreaks for row crops. California Agriculture: November.

Schultz HB, Carlton AB, Lory F. 1963. Interpolating methods for wind erosion protection in San Joaquin asparagus. California Agriculture: September.

Shlemon RJ, Begg EL. 1975. Late Quaternary Evolution of the Sacramento–San Joaquin Delta, California. In: Suggate RP, Cressel MM, editors. Quaternary studies. Bulletin 13. Wellington (New Zealand): The Royal Society of New Zealand p 259–266.

Stephens JC, Allen LH, Chen E. 1984. Organic soil subsidence. In: Holzer TL, editor. Man-induced land subsidence. Reviews in Engineering Geology, Vol. VI. Boulder (CO): Geological Society of America.

Stephens JC, Stewart EH. 1976. Effect of climate on organic soil subsidence. IAHS Publication 121:649–655.

Tate RL III. 1979. Effect of flooding on microbial activities in organic soil: carbon metabolism. Soil Science 128:267–273.

Tate RL III. 1980a. Microbial oxidation of organic matter of histosols. Advances in Microbial Ecology 4:169–201.

Tate RL III. 1980b. Effect of several environmental parameters on carbon metabolism of inceptosols. Microbial Ecology 5:329–336.

Terzaghi K. 1925. Principles of soil mechanics. IV: settlement and consolidation of clay. Engineering News Record, Vol. 95. New York (NY): McGraw–Hill.

Thompson J. 1957. The settlement geography of the Sacramento–San Joaquin Delta, California [dissertation]. [Palo Alto (CA)]: Stanford University.

Tugel AJ. 1993. Soil Survey of Sacramento County. U.S. Department of Agriculture, Soil Conservation Service.

Volk BG. 1973. Everglades histosol subsidence. 1. CO_2 evolution as affected by soil type, temperature, and moisture. Proceedings of the Soil and Crop Science Society of Florida 32:132–135.

Weir WW. 1950. Subsidence of peat lands of the Sacramento–San Joaquin Delta, California. Hilgardia 20:27–56.

Welch LE. 1977. Soil survey of Contra Costa County, California. U.S. Department of Agriculture, Soil Conservation Service.