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Subsidence of agricultural lands in the Sacramento-San Joaquin Delta, California: Role of aqueous and gaseous carbon fluxes

Steven J. Deverel
Davis, California

Stuart Rojstaczer
Department of Geology and Center for Hydrologic Science, Duke University, Durham, North Carolina

Abstract. To examine the causes of land subsidence on marshes drained for agriculture, carbon fluxes and changes in land-surface elevation were determined on three islands in the Sacramento-San Joaquin Delta, California. Over the time period of March 1990 to May 1992, gaseous CO_2 fluxes were determined approximately monthly using closed chambers, and dissolved carbon fluxes were determined from the dissolved carbon loads of drainage ditches adjacent to each field site. Surface elevation changes were measured continuously by measuring the distance between the land surface and an elevated structure anchored beneath the organic soil layer. Gaseous CO_2 fluxes accounted for most of the permanent subsidence measured over the monitoring period. Gaseous CO_2 fluxes are strongly affected by soil temperature. Net subsidence rates for the three islands, which have different depths of organic soils and water-management practices, range from 0.46 to 1.06 cm/yr. Estimates of dissolved organic carbon fluxes for all three islands were small relative to gaseous CO_2 losses and represent <1% of the measured subsidence.

Introduction

Oxidation and associated subsidence of organically rich soils induced by agricultural drainage are worldwide problems that create local flood hazards and have a significant impact on the global carbon cycle [*Rojstaczer and Deverel*, 1993; *Stephens et al.*, 1984; *Armentano*, 1980]. In the Sacramento-San Joaquin Delta, marshes and swamps were drained for agriculture beginning in the latter part of the nineteenth century and have undergone continuous subsidence since that time (Figure 1) [*Weir*, 1950; *Prokopovitch*, 1985]. The subsided lands are somewhat imperfectly maintained free of inundation by the installation and maintenance of levees and by networks of drainage ditches. As subsidence continues, the potential of flooding due to levee breakage increases significantly. Several levee breakages in the past century were never repaired and have caused permanent inundation of the agricultural land [*Rojstaczer and Deverel*, 1995; *Hundley*, 1992].

While such flooding causes obvious local damage, the location of the delta makes flooding a potentially significant regional problem. The delta is the transfer point for the majority of agricultural and municipal water supplied to southern California. The system of levees and islands in the delta impedes the movement of brackish water landward and usually allows transfer of relatively fresh water to the California Aqueduct [*Hundley*, 1992]. Extensive damage to the levees with concomitant flooding of the agricultural land can cause significant landward movement of brackish water and threatens the quality and usage of delta-derived water.

While the principal cause of land subsidence in this region is generally believed to be oxidation of soil carbon, processes such as mechanical compaction, wind erosion, anaerobic decomposition, and dissolution of carbon also have been cited as significant contributors to subsidence of organic soils [e.g., *Weir*, 1950; *Prokopovitch*, 1985]. The role of presumed auxiliary processes, however, has never been measured in the field. If processes such as dissolution of carbon and anaerobic decomposition are relatively insignificant, then the potential for future subsidence of these lands may be abated by the return of these agricultural lands to wetland habitat.

The relationship between land subsidence and drainage of marsh land has been studied extensively, but most of the work concentrated on laboratory and field measurement of soils from the Florida Everglades. The rates of CO_2 production in the laboratory for soils from the Florida Everglades increase with increasing temperature (between 10° and 60°C) and increasing organic carbon content of the soil; rates of CO_2 production decreased with increasing soil moisture [*Knipling et al.*, 1970; *Volk*, 1973]. *Tate* [1979, 1980a, b] reported similar results in his studies of microbial activity in organic soils in the Florida Everglades. The rates of CO_2 production in the laboratory agree qualitatively with the rate of field-measured subsidence in The Everglades. This agreement suggests that most subsidence in the Florida organic soils is the result of biochemical oxidation [*Stephens and Stewart*, 1976].

Although the laboratory measurements noted above are extremely useful, these results should be applied cautiously to the delta. Historical subsidence rates are significantly higher in the delta, and the causes for the difference are not known [*Broadbent*, 1960]. Development of sound management practices for maintenance of delta lands requires that the relationship between oxidation of organic soil and land subsidence be well

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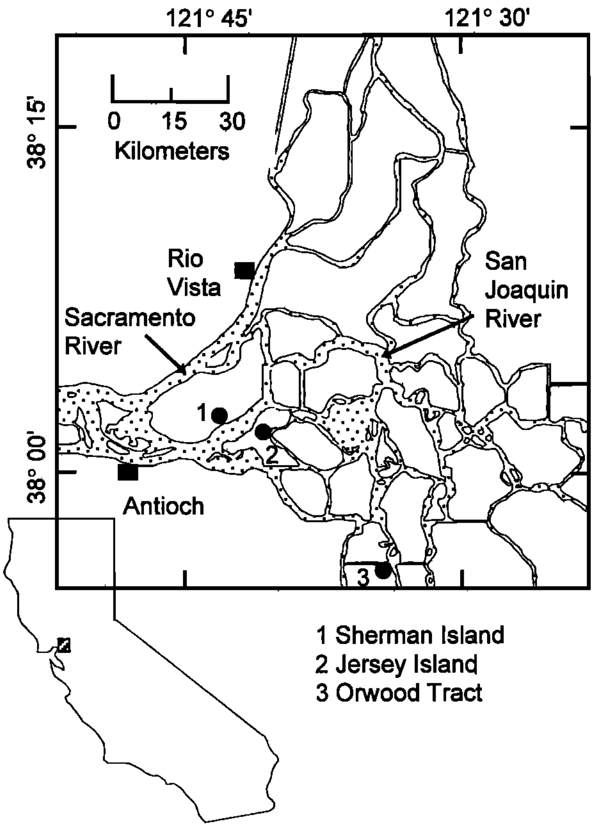

Figure 1. Location of the Sacramento-San Joaquin Delta. Islands in the delta are below sea level and are maintained by a 2200-km network of levees. Locations of field sites are also shown.

understood. It also requires the measurement of the impact of auxiliary processes such as carbon dissolution on land subsidence.

This paper presents the results of measurements of contemporary rates of subsidence and carbon fluxes in the delta from March 1990 to May 1992. We examine the degree to which (1) gaseous carbon fluxes are related to subsidence, (2) soil temperature and soil moisture influence carbon fluxes, and (3) aqueous carbon fluxes influence subsidence. Our approach differs from similar work in the Florida Everglades in that we measured both subsidence and carbon fluxes directly in the field over time. To measure land subsidence, we installed continuous-record extensometers [*Riley*, 1986] on three islands where depth of the organic soils, cropping, and water-management practices are different. In the agricultural fields adjacent to the extensometers we measured CO_2 fluxes from the soil surface and the outflux of dissolved organic carbon (DOC) in drain water. The time series of subsidence and CO_2 fluxes were examined as a function of soil temperature and soil moisture. Finally, subsidence estimated from CO_2 fluxes was compared with measured changes in land-surface elevation.

Description of Field Sites

Sites on three islands (Jersey Island, Orwood Tract, and Sherman Island) (Figure 1) were selected to represent a range of environments and land use practices that we thought would affect oxidation and subsidence. All three islands are drained through a network of open ditches. Five specific locations were established in agricultural fields on each of the three islands for approximately monthly measurements of CO_2 fluxes, soil temperature, and soil moisture content.

At the Jersey Island field site, ~3 m of organic soil overlies a reduced coarse-grained substratum. This site is located in a 5.8-ha field that was planted with corn in 1986 but has not been cultivated since. Over the time period of this study the primary vegetation was Bermuda grass (*Cynodon dactylon*). The water table is almost always within 1.5 m of the land surface and was within 30 cm of the land surface for several months during the year.

At the Orwood Tract field site, 0.6–1.3 m of organic soil overlies a reduced organic clay substratum. The site is located on the edge of a 22.1-ha field that was permanently planted with asparagus (*Asparagus officinalis*). The water table fluctuates but generally was at depths >1.0 m below the land surface.

At the Sherman Island field site, 7.6 m of organic soils and sediment overlies a reduced clay with organic lenses. The site is located in a 26.1-ha field that was planted with wheat (*Triticum aestivum*) in 1990, which was harvested in July 1990. The field was fallowed and cultivated from July 1990 through May 1992. The water table was consistently at depths >0.7 m below the land surface.

Methods

CO_2 Flux

The rate that CO_2 concentrations increased in a closed chamber provided the data for calculating the CO_2 flux from the soil [*Rolston*, 1986] at each of five sites on Jersey and Sherman Islands and Orwood Tract. The chamber is a cylinder 92 cm in diameter and 23 cm high and is constructed out of 22-gauge sheet metal. A ring of angle iron was attached to the outside of the chamber 5 cm from the open end to ensure that the chamber was set to the same depth at each site. The top of the chamber had a sampling port in the center of the chamber as well as three equally spaced ports near the outer edge of the chamber. Rubber septa were used to seal each of the ports except for the port with the 17.8 × 1.25 cm (outside diameter) copper tube that provided pressure equalization [*Hutchinson and Mosier*, 1981]. A draft cap was placed on this port with the tube to prevent the wind from blowing across the open tube. Gas samples were taken from the center port, and wire from a thermocouple was placed under the septum of an outside port. To reduce wind infiltration through the soil [*Matthias et al.*, 1980], the chamber was covered with a large tarp (2.2 × 2.8 m) with the edges weighted down with lengths of chain. A large umbrella was used to shade the chamber, and it reduced radiant heating.

To estimate the CO_2 flux from the soil, the CO_2 concentration was determined in 1- to 2-mL gas samples collected four times from the chambers during 20-min sampling periods. Prior to setting the chamber and collecting the gas samples the surface vegetation was cleared from the area. The soil CO_2 flux was estimated based on the increase in CO_2 concentrations in the chamber. Various experiments were conducted to determine the potential stratification of CO_2 concentrations in the chamber by sampling at different locations in the chamber. The results of these experiments indicated that the chamber design allowed for complete mixing within the chamber during the CO_2 measurements. CO_2 flux measurements were made once during the approximately monthly field trips. The measurements were taken during midmorning or early afternoon. A duplicate measurement was taken at one site in each field after all the measurements had been made. A diurnal sampling in the fall of 1991 indicated that there is a 50–100% daily variation in CO_2 fluxes.

The portions of CO_2 derived from organic matter decomposition and plant root respiration were estimated from determinations of $^{13}C/^{12}C$ ratios and ^{14}C concentrations in gas samples collected in 2-L sampling vessels evacuated to 10^{-6} atm. The vessels were opened to collect chamber gas after the chambers were placed on the soil for about 0.5 hour. Gas from the chamber flowed from the chamber into the vessel at a flow rate of ~1 L/h. The vessels were removed after ~2 hours. The samples for isotope composition were collected from chambers placed in the field in June and November 1990. The $^{13}C/^{12}C$ ratios were determined in cryogenically separated CO_2 in the U.S. Geological Survey (USGS) Isotope Laboratory in Menlo Park, California, with a Neir type, 30 cm, 90° triple collecting ratio mass spectrometer. The ^{14}C concentrations were determined in gas samples at the tandem mass accelerator at the University of Arizona Faculty of Science. The results of these analyses are tabulated and discussed by *Rojstaczer and Deverel* [1993]. The results of these analyses indicated that ~50% of the CO_2 flux was due to root respiration during February–November when there was active plant growth. We assumed that all of the CO_2 was the result of organic matter oxidation during December and January when there was no plant growth.

The temperature in the chamber during the CO_2 flux measurements was measured with an Omega Model 450 AKT thermocouple and a Chromel-Alumel thermocouple each time a sample was withdrawn. These temperature data were used to make ideal gas law corrections for volume changes caused by temperature changes during the experiment. Temperature measurements made inside the chamber did not vary more than ±3°C during the flux measurements. During each measurement another thermocouple thermometer encased in a steel rod (also manufactured by Omega) was inserted 30 cm into the soil at each flux measurement site to measure the soil temperature.

Gas samples were analyzed for CO_2 using a portable 12-V gas chromatographic (GC) equipped with a thermal conductivity detector manufactured by Mircrosensor Technology. Samples were swept by the helium carrier gas into a 25 cm × 0.5 mm ID HayeSep A column that was held at 55°C. The GC was equipped with a thermal conductivity detector. The detector's response was read as peak height and was compared to the response of known concentrations of CO_2 mixed with air. Atmospheric CO_2 concentration was variable and hence unsuitable for calibration. A set of three calibration standards was run for each flux measurement. Four measurements taken 5 min apart were sufficient to determine the rate at which the CO_2 concentration increased.

Dissolved Organic Carbon Flux, *p*H, and Specific Conductance

Water samples were collected for determination of DOC and organic carbon fractionation in the drainage ditches adjacent to each field site. When there was flow in the drainage ditches, the flow velocity was measured with an electromagnetic velocity meter placed in the outflow pipe that led into a main drain on Sherman Island and Orwood Tract (velocity meters have an accuracy of ±0.0030 m/s). The cross-sectional area of flow was calculated from the internal geometry of the pipe and the measured height of flow in the pipe. The flow was calculated as the product of the velocity and the cross-sectional area of flow.

For Jersey Island we were unable to measure flow in the drainage ditch. We estimated the volume of water leaving the field from changes in water levels at two locations in the field. The average decline in water level multiplied by an estimated porosity of 0.4 and the area of the field (5.1 ha) was assumed to represent the volume of water leaving the field.

Samples for determination of DOC were pressure-filtered through a 0.45-μm silver membrane filter into a glass sample bottle and packed in ice until analysis. Concentrations of DOC were determined with methods described by *Wershaw et al.* [1987]. The DOC was fractionated into hydrophobic and hydrophilic fractions with methods described by *Leenheer and Huffman* [1979].

Samples for determination of *p*H and specific conductance were collected in a standard USGS sampling churn from the drainage ditches adjacent to all three fields. Prior to collection of samples the churn was thoroughly rinsed with the water in the ditch. The *p*H and specific conductance were determined in water that was allowed to flow from the churn spigot into plastic containers. The *p*H and specific conductance were measured with portable meters that were calibrated at each site with standardized solutions. In the case of the specific conductance the standardized solutions were within 300 μS/m of the sample.

Soil Moisture, Soil Organic Content, Water Table Land-Surface Elevation, and Soil Bulk Density

Soil moisture content was determined with a neutron moisture probe that was calibrated in the field to volumetric content (cm^3 H_2O/cm^3 soil) as described by *Bell and McCulloch* [1983]. Percentage of organic matter in soil samples was determined by loss on ignition as described by *Nelson and Sommers* [1982]. Soil bulk density was determined by the core method described by *Blake and Hartge* [1986] at each CO_2 sampling site.

Water table elevation was determined at each site with a vented Druck silicon strain bridge pressure transducer (300-mbar range relative to atmospheric pressure) submerged in 2.5-m-deep wells with slotted 5.1-cm-diameter casing. The transducers were connected to data loggers (Campbell CR10) and sampled hourly. DC-DC displacement transducers (Sangamo linear variable differential transformer, 5.1-cm range) were also connected to the data loggers and measured the changes in land-surface elevation relative to a structure anchored below the organic soil.

The structure for elevation control consisted of three piers of 3.1-cm-diameter steel pipe inserted into 5.1-cm-diameter polyvinyl chloride (PVC)-cased holes which formed a triangle with 2-m-length sides and which were drilled to a depth 1.5 m below the organic soil layer. After insertion to the bottom of the holes each steel pipe was hydraulically pushed to refusal in the underlying mineral soil using a drill rig. The three piers exposed above the land surface were cut until their tops formed a horizontal plane, and angle iron was welded onto the pipe to form a triangular frame. The body of the displacement transducer was attached to the angle iron, and the rods were connected to the land surface with 0.6-cm-thick, 100 cm^2 aluminum plate that rested on the soil. Hence measured land surface changes did not reflect any soil loss due to wind erosion.

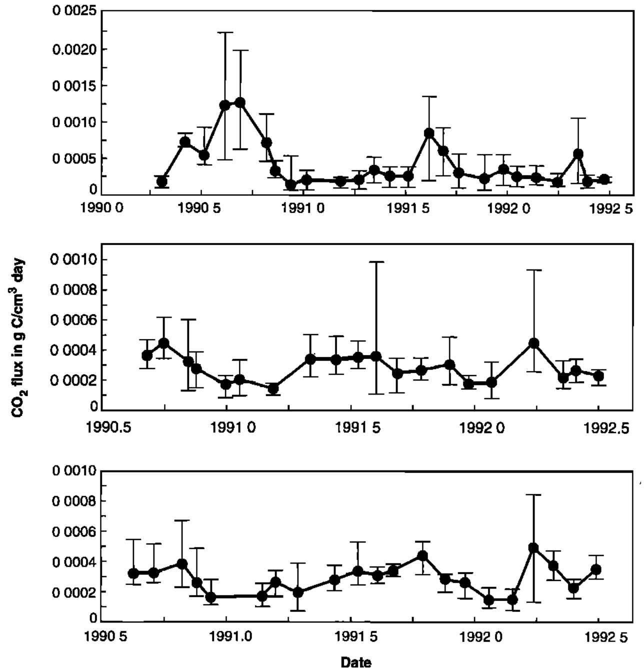

Figure 2. CO_2 fluxes measured on Jersey Island, Sherman Island, and Orwood Tract, March 1990 to May 1992. Solid circles represent the arithmetic average of measurements at five sites on each island or tract and the bars represent the range of the data.

Results and Discussion

CO_2 Fluxes

The average and range of CO_2 fluxes measured at the sites in the field on each island during the study period are shown in Figure 2. CO_2 fluxes at all three field sites generally increased to maximum values during the spring and summer and decreased to minimum values in the fall and winter. Spatial and temporal variability in CO_2 flux was affected by soil temperature, soil moisture, soil organic matter content, and plant root respiration. Soil temperature appears to be the primary factor, as it explains a large percentage of the variance in CO_2 fluxes (32–48%) for all three islands.

Figure 3 shows the temporal variability in soil temperature on each island. The logarithm of CO_2 flux and soil temperature at 30 cm depth is significantly correlated ($\alpha = 0.001$) for all measurements made on Jersey Island ($r^2 = 0.48$), Orwood Tract ($r^2 = 0.47$), and Sherman Island ($r^2 = 0.32$) (Figure 4). The soil temperature relation is generally consistent with measurements made by *Jenny* [1930] that indicate that soil microbial activity approximately doubled for each 10° increase in temperature above 5°C. The Jersey, Orwood, and Sherman regression equations indicate that the CO_2 flux increases 2.4, 1.7, and 1.6 fold, respectively.

The CO_2 flux-temperature relation is also influenced by soil moisture. Figure 5 shows the relation of CO_2 fluxes, soil temperature, and soil moisture determined at 30 cm for all sites on Jersey, Sherman, and Orwood. The points on Figure 5a represent different ranges of CO_2 fluxes divided by the mean CO_2 flux for each site. In general, CO_2 fluxes above the mean were measured when soil temperatures were above 12.5°C and soil moisture was above 0.30 cm³/cm³. Most of the CO_2 fluxes above the mean were measured when soil moisture values were between 0.30 and 0.55 cm³/cm³. The one exception is the CO_2 flux measured when the soil temperature was over 25°C.

The data in Figure 5a indicate that soil temperature and moisture content values between 12.5° and 25°C and 0.30 and 0.50 cm³/cm³ represent the range in which CO_2 fluxes were greater than average at all sites. Figure 5b indicates that almost all of the fluxes above the mean for each site were measured when the moisture content was between 0.28 and 0.52 cm³/cm³. Soil temperatures are generally within this optimum range from May through October. Soil moisture conditions vary substantially depending on irrigation and rainfall, but generally, moisture conditions are in this range during the spring and summer when the maximum fluxes were measured. A combination of saturated soil conditions and low soil temperatures caused CO_2 fluxes to remain low during the late fall, winter, and early spring. Higher CO_2 fluxes resulted from low soil moisture contents and higher temperatures during the late spring, summer, and early fall.

At Jersey Island, CO_2 fluxes and soil temperatures were lower in the spring and summer 1991 relative to the same periods in 1990. The measured soil temperatures during April–October 1991 (median of 17.7°C) were significantly lower than the 1990 temperatures during the same months (median of 18.7°C), as determined by the Mann-Whitney rank sum test. Hence the lower CO_2 fluxes in 1991 appear to be temperature related.

At Sherman Island the relation between soil temperature and CO_2 flux is somewhat similar to the relations observed on Jersey Island and Orwood Tract, but the correlation of the logarithm of CO_2 flux with soil temperature explains less (32%) of the variance. The CO_2 flux on Sherman Island seems to be affected by drying and cracking of the soil caused by a lack of irrigation. Large CO_2 flux values were measured during the summer 1991 and winter 1992 at two of the five measurement points. Measurements were taken when cracks were visible near the chamber sites. The cracks extend to as much as 1 m in depth, where CO_2 in the soil gas can reach levels as high as 10%. CO_2 fluxes from these cracks probably are much larger than fluxes measured where there are no cracks because the cracks allow degassing of areas of high CO_2. Subsurface cracks that are not visible at the surface also form in delta organic soils as they desiccate [*Hansen and Carlton*, 1985]. The subsur-

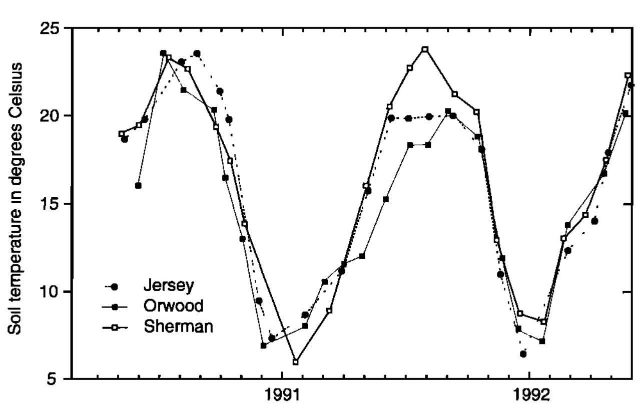

Figure 3. Soil temperatures measured at 30 cm depth on Jersey Island, Orwood Tract, and Sherman Island, May 1990 to May 1992. Solid circles, solid squares, and open squares represent the arithmetic average of measurements at five sites on each island or tract.

face cracks may cause CO$_2$ fluxes to vary more independently of soil temperature than at the other sites.

Aqueous Carbon Fluxes

In addition to the gaseous loss of CO$_2$, there is also a mobilization and loss of DOC as water percolates through the unsaturated zone. Table 1 shows DOC values, flows, carbon loads, and calculated subsidence rates. Because of the relatively high DOC and flows at the Jersey Island site during the spring the organic carbon load is high relative to the loads from Sherman Island and Orwood Tract sites.

The organic carbon load from the Jersey Island site is high because of the high water table in the winter and early spring and the large change in the water table in the spring and summer. The water table rises close to the land surface in the winter and early spring and is in prolonged contact with well-decomposed organic matter within 100 cm of land surface, resulting in high DOC concentrations in the drain water. The gradual decrease in the depth to groundwater during the spring results in a loss of organic carbon from the field through the drainage ditch.

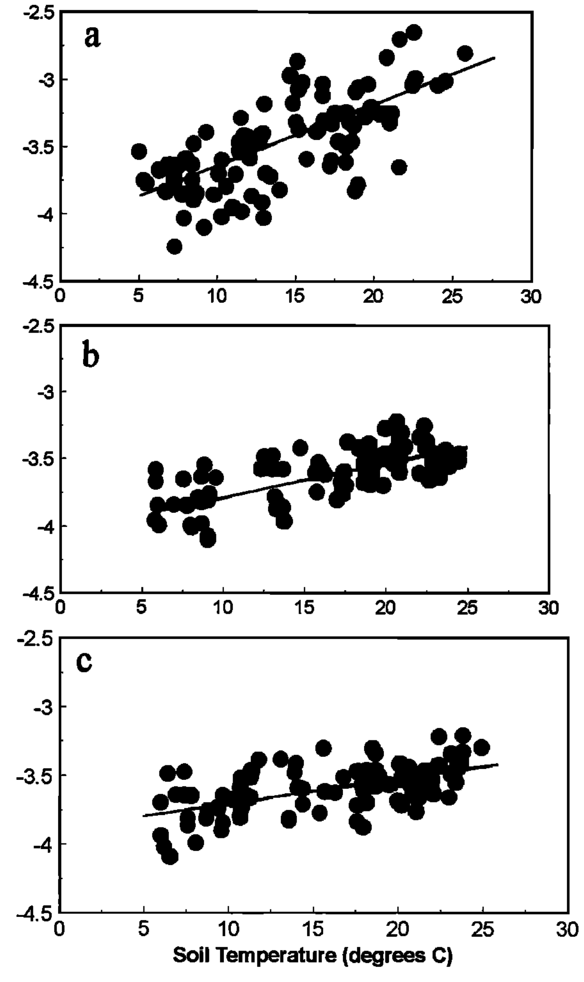

Figure 4. Relation of CO$_2$ flux (g C/cm^2 d) and soil temperature for (a) the Jersey Island, (b) Orwood Tract, and (c) Sherman Island sites. Regression equation for Jersey Island is $\log_{10} \mathrm{CO}_2 = 0.0453T - 4.12$ with $r^2 = 0.48$ (where T is temperature in degrees Celsius). Regression equation for Orwood Tract is $\log_{10} \mathrm{CO}_2 = 0.02354T - 3.999$ with $r^2 = 0.47$. The regression equation for Sherman Island is $\log_{10} \mathrm{CO}_2 = 0.01841T - 3.89$ with $r^2 = 0.32$.

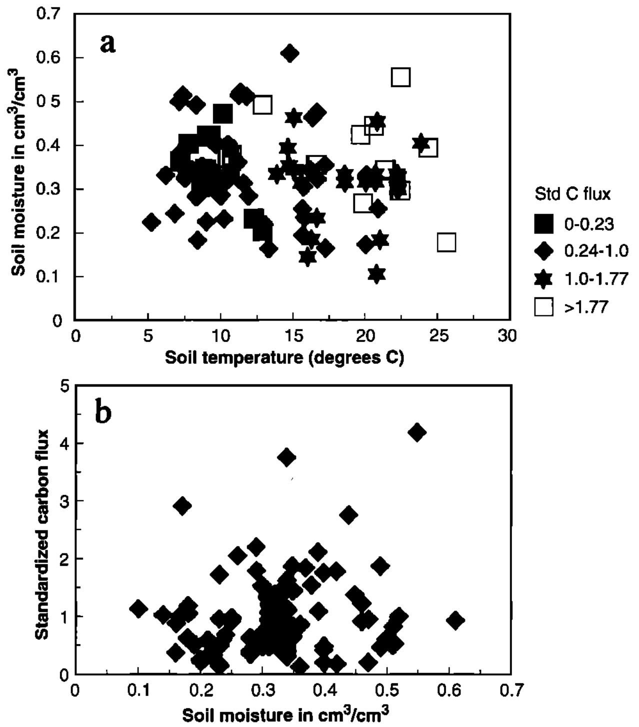

Figure 5. Relation of standardized CO$_2$ fluxes (CO$_2$ fluxes are divided by the mean flux at each site) to (a) soil moisture and temperature and (b) soil moisture measured at 30 cm.

Prolonged proximity of the water table to the land surface also results in evapoconcentration of the groundwater, which may contribute to high DOC and high salinity (median specific conductance is 5985 μS/cm). In contrast, the water table at the Orwood Tract and Sherman Island sites is maintained at deeper depths by better functioning drainage systems. The groundwater collected by the drainage ditches is in contact with fibrous, relatively less composed organic soil on Sherman Island and mineral substrata on Orwood Tract. The median drain water salinities also are considerably lower (680 μS/cm for Orwood Tract and 1813 μS/cm for Sherman Island).

The composition of DOC as determined by fractionation into acidic, basic, and neutral hydrophobics and hydrophilics provides additional information about the processes affecting DOC concentrations in drain water from the three field sites. For three samples collected from the Jersey Island drainage ditch, 53–69% of the DOC was in the form of hydrophilic acids, which generally are short-chained carboxylic acids [*Thurman*, 1985]. The remainder of the DOC was primarily acidic and neutral hydrophobic compounds. The DOC in drain water samples collected from Orwood Tract ranged from 26 to 51% hydrophilic compounds. Similarly, 27–45% of Sherman Island DOC is hydrophilic acid; the remaining DOC is primarily acidic and neutral hydrophobic compounds.

The greater proportion of hydrophilic acids in the DOC from Jersey Island apparently results from prolonged contact with more decomposed organic soil near the land surface. This also results in a lower *p*H (3.5–5.5) in samples from Jersey Island relative to samples (6.5–7.0) from Orwood Tract and Sherman Island.

Table 1. Dissolved Organic Carbon Concentration, Flow, and Carbon Loads in Drainage Ditches and Calculated Subsidence Rates From the Carbon Loads for the Three Islands

Date	Dissolved Organic Carbon, mg/L	Flow, L/d m^2	Load, g C/d m^2	Calculated Subsidence Rate, cm/yr
		Jersey Island		
May 2, 1990	64	3.76	0.24	3.6×10^{-2}
May 19, 1990	110	3.76	0.41	6.1×10^{-2}
June 5, 1990	48	3.76	0.18	2.7×10^{-2}
June 27, 1990	96	3.76	0.36	5.4×10^{-2}
July 12, 1990	87	3.76	0.32	4.7×10^{-2}
		Orwood Tract		
May 9, 1990	17.0	0.131	0.0024	7.8×10^{-4}
Oct. 18, 1990	16.0	0.214	0.0034	1.2×10^{-3}
Jan. 22, 1991	10.2	1.303	0.0133	4.6×10^{-3}
Feb. 12, 1991	10.1	0.940	0.0095	3.3×10^{-3}
March 13, 1991	10.2	1.121	0.0114	4.0×10^{-3}
May 7, 1991	14.0	0.009	0.096	4.6×10^{-4}
		Sherman Island		
May 18, 1990	24.0	0.050	0.0012	4.7×10^{-4}
June 13, 1990	14.0	0.002	0.00002	9.2×10^{-6}
Aug. 24, 1990	7.2	0.004	0.00003	1.3×10^{-5}
Oct. 2, 1990	24.1	0.051	0.0012	4.8×10^{-4}
Nov. 29, 1990	34.2	0.153	0.0052	2.1×10^{-3}

Changes in Land-Surface Elevation

Changes in land-surface elevation on each of the three islands are related to CO_2 losses and changes in water levels. Figure 6a shows changes in land-surface elevation and water levels for the Jersey Island extensometer site. Fluctuations in land-surface elevation correspond to fluctuations in water levels, but there was a net decrease in land-surface elevation of 1.01 cm from late April 1990 to late February 1992; water level values were nearly equal at these times. This decrease in land-surface elevation corresponds to a subsidence rate of ~0.55 cm/yr. Measurement between the points of equal water level from mid-November 1990 to January 1992 resulted in an annual subsidence rate of 0.68 cm/yr.

The proportion of the measured CO_2 flux resulting from organic matter oxidation at the extensometer site was estimated using the isotope data of *Rojstaczer and Deverel* [1993]. We assumed that 50% of the measured CO_2 flux was due to organic-matter oxidation during February–November when the Bermuda grass was actively growing. The measured CO_2 flux was assumed to be entirely the result of organic matter oxidation in December and January. Also, the estimated average carbon flux between measurements was adjusted to account for data that indicated that CO_2 fluxes decreased ~50% during the night and early morning.

Subsidence calculated from CO_2 loss is plotted on Figure 6a for Jersey Island. The elevation change was calculated by first estimating an average daily CO_2 flux between measurements. This CO_2 flux measurement was used to estimate a daily subsidence rate by dividing by the soil bulk density (g/cm^3) and soil organic matter content (grams organic matter per gram soil) and multiplying by the percent carbon of the soil organic matter (assumed to be 0.5 g C/g organic matter [*Broadbent*, 1960]). CO_2 fluxes used to calculate subsidence prior to August 1990 were based on initial measurements made only at the extensometer site and are not shown in Figure 2. The average soil bulk density of samples collected near the extensometer was 0.96, and organic matter content was 20.0%. Subsidence calculated from CO_2 fluxes agrees reasonably with subsidence measured by the extensometer transducer.

Measured subsidence rates were similar at Orwood Tract (Figure 6b). Fluctuations in water table elevation account for most of the fluctuations in land-surface elevation, but net subsidence was 1.02 cm from early April 1990 to late March 1991 when hydraulic head values were about equal. This corresponds to a net subsidence rate of ~1.06 cm/yr. Net subsidence from late June 1990 to December 1991 was ~1.4 cm or ~0.8 cm/yr. Subsidence calculated from CO_2 fluxes for the Orwood Tract extensometer site was determined in the same way as on Jersey Island. Average bulk density was 0.85, and organic matter content was 24.4%. Measured net subsidence generally corresponds to subsidence calculated from CO_2 fluxes, but the calculated subsidence generally underestimates the amount of subsidence.

On Sherman Island, measured subsidence is relatively unaffected by the small water table elevation fluctuations. Figure 6c shows that land-surface elevation decreased steadily until October 1990 and remained essentially constant until March 1991. Measured land-surface elevation abruptly increased 0.2 cm in September 1990 for no known reason. The instrument shelter, which was leaning on the extensometer angle iron structure at that time, was removed. This may have bent the structure slightly. Hydraulic head values increased in December (Figure 6c) when soil temperatures and CO_2 fluxes were low and resulted in no net elevation changes. Decreasing hydraulic head values resulted in decreasing land-surface elevation in April and May 1991. Net subsidence from late May 1990 to mid-February 1992 was ~0.85 cm (including the 0.2 cm increase in September 1990) or 0.46 cm/yr. Estimated subsidence on Sherman Island from CO_2 fluxes (average bulk density of 0.85; organic matter content of 28.0%) agrees well with subsidence measured at the extensometer site.

The comparison of the annual rates of subsidence estimated based on carbon fluxes and extensometer measurements is shown in Table 2. The estimates based on carbon fluxes were

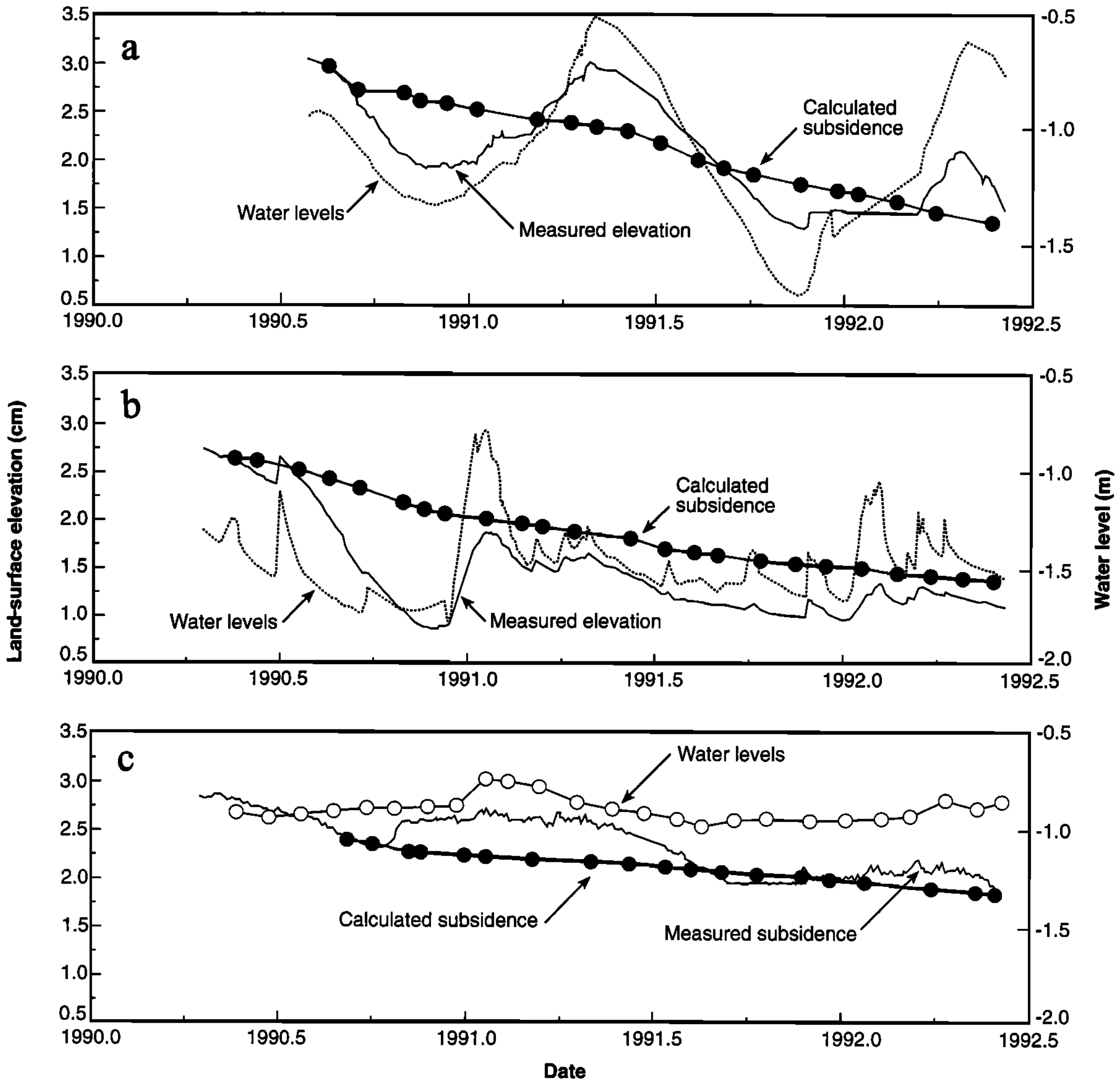

Figure 6. Measured changes in land-surface elevation and water levels and estimated elevation changes based on CO_2 fluxes at the extensometer sites on (a) Jersey Island, (b) Orwood Tract, and (c) Sherman Island.

determined for the entire period of record, and the measured rates are based on the decrease in elevation between points of equal water levels. The estimated and measured values generally agree.

The measured subsidence at the extensometer at all three sites is highly dependent on water level fluctuations, and regression analysis was conducted to further evaluate the relation between water levels, land-surface elevation changes, and subsidence estimates based on carbon fluxes. First, the subsidence not related to water level changes was estimated by regressing land-surface elevation changes on water levels. For the Orwood data there was a logarithmic relation between the water level and land-surface elevation data; the relation was linear for Jersey and Sherman. For all three islands the residuals were normally distributed over the range of the data. Next, the residuals from this analysis were linearly regressed against subsidence calculated from carbon fluxes. This relation explained 76, 60, and 63% of the variance for the Jersey, Orwood, and Sherman data, respectively. In all three cases the correlations between the residuals and subsidence calculated from carbon fluxes were significant ($\alpha = 0.001$).

Uncertainty and error in the carbon-flux-based estimates of subsidence include the portion of CO_2 flux derived from organic matter oxidation and plant-root respiration and the temporal variability in CO_2 fluxes. Our isotope analysis provided little information about the temporal variability in the relative proportion of plant-root respiration and organic matter oxidation in the CO_2 flux. The diurnal fluctuation in CO_2 fluxes was accounted for in the subsidence estimate by assuming that the

Table 2. Measured Subsidence Rates and Estimated Subsidence Rates Based on CO_2 Fluxes for the Three Islands

Island	Measured Subsidence Rate, cm/yr	Calculated Subsidence Rate, cm/yr
Jersey	0.68	0.92
Orwood	0.80	0.62
Sherman	0.46	0.32

CO_2 fluxes decreased by 50% during the night and early morning. This was based on one set of hourly diurnal flux measurements at one site on Jersey Island, and the diurnal changes in CO_2 fluxes probably varied seasonally and by site.

Rojstaczer and Deverel [1995] noted that historical subsidence rates from 1910 to 1988 slowed with time on Sherman Island. Both the measured and CO_2 fluxes inferred subsidence for Sherman Island are lower than the rate of subsidence over the time period 1952–1988 on Sherman Island (35 cm total subsidence or an average of 1.0 cm/yr) for soils having organic matter percentages close to those measured during this study (22–28%) [*Rojstaczer and Deverel*, 1995]. The difference in rates between the contemporary and historical subsidence indicates that subsidence rates continue to slow with time. The decreased rate of subsidence of Sherman Island corresponds with decreasing rates of subsidence in the central delta [*Rojstaczer and Deverel*, 1993]. As noted earlier [*Rojstaczer and Deverel*, 1993], the correspondence between contemporary subsidence and carbon loss indicates that oxidation-induced subsidence is largely due to a decrease in the percentage of carbon, rather than a collapse of pore space.

Estimates of subsidence owing to aqueous organic carbon loss were based on the assumption that carbon in the form of DOC is mobilized in the saturated and unsaturated zone, causing a decrease in land-surface elevation. For each field we based the subsidence estimates on average bulk density values and organic matter contents. Subsidence estimates shown in Table 1 generally are small relative to the subsidence rates measured by the extensometers. Subsidence rates and CO_2 fluxes estimated for Jersey Island were higher because the measured DOC concentrations and the flow estimates were higher. Subsidence rates estimated for Orwood Tract and Sherman Island (Table 1) were smaller because measured DOC concentrations were low. Annual subsidence rates for Jersey Island were estimated assuming that flow took place only from May through July 1990.

Summary and Conclusions

Land-surface elevations changes, CO_2 fluxes, and environmental factors were measured and evaluated as part of a study of the causes of subsidence in organic soils on Jersey Island, Orwood Tract, and Sherman Island in the Sacramento-San Joaquin Delta, California. The strongest component of changes in land-surface elevation determined with extensometers is seasonal and influenced primarily by seasonal water table elevation changes. Sixty to 76% of the variance in land surface elevations that are not influenced by changes in water levels can be explained by carbon losses in the form of gaseous CO_2 fluxes, indicating that this is the major cause of permanent subsidence. Permanent subsidence rates were 0.68 cm/yr on Jersey Island, 0.80 cm/yr on Orwood Tract, and 0.46 cm/yr on Sherman Island. These rates agreed well with subsidence rates estimated from CO_2 fluxes.

CO_2 fluxes were significantly correlated with soil temperature measured at 30 cm and were also influenced by soil moisture. Between 32 and 47% of the variance in CO_2 fluxes was explained by soil temperature variations. The regression for CO_2 fluxes and soil temperature indicated that CO_2 fluxes increase from 1.6 to 2.4 fold with 10° increases in temperature. Most of the CO_2 fluxes that were above the mean were measured when soil moisture values were between 0.30 and 0.55 cm^3/cm^3. Soil moisture and temperature are within the optimum ranges during the late spring, summer, and early fall when the highest fluxes were measured. A combination of saturated soil conditions and low soil temperatures caused CO_2 fluxes to remain low during the late fall, winter, and early spring.

Estimates of DOC fluxes for all three sites were small relative to gaseous CO_2 losses and represent <1% of the measured subsidence. The consistently high water table in contact with well-decomposed organic matter on Jersey Island results in high-DOC fluxes, lower drain water *p*H values, and higher proportions of hydrophilic organic acids than for Orwood Tract and Sherman Island.

The results presented here have implications for management issues associated with drainage of organic soils in this and other regions. The temperature and moisture regime measured in the drained agricultural soils is conducive to large CO_2 fluxes during the spring, summer, and fall, and these conditions have contributed substantially to the subsidence in the organic soils in the Sacramento-San Joaquin Delta. Changing the soil temperature and moisture regime so that soils are wetter and cooler will probably reduce subsidence. It should be noted that the contemporary rates of elevation loss measured here are lower than those that have been measured in this region in the past and are consistent with inferred slowing of subsidence rates over the last 80 years [*Rojstaczer and Deverel*, 1993, 1995].

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S. J. Deverel, P.O. Box 2401, Davis, CA 95617. (e-mail: sdeverel@davis.com)

S. Rojstaczer, Department of Geology and Center for Hydrologic Science, Duke University, Box 90230, Durham, NC 27708. (e-mail: stuart@geo.duke.edu)

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