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TIME DEPENDENCE IN ATMOSPHERIC CARBON INPUTS FROM DRAINAGE OF ORGANIC SOILS

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Abstract. Historical and contemporary subsidence in the San Joaquin-Sacramento Delta, California indicates that subsidence rates associated with drainage of organic soils have declined over time. Contemporary measurements of carbon flux into the atmosphere can be used to predict contemporary rates of permanent subsidence. This correspondence indicates that most subsidence is caused by carbon oxidation. The current contribution of atmospheric carbon from the Delta is 2 x 10^{12} gm C/yr. This estimate is a factor of 3-4 less than previous estimates and reflects the declining rate of CO_2 production in the Delta over the last several decades. Estimates of current production of CO_2 from other drained agricultural lands that are based upon time-averaged historical rates of subsidence are also likely to be too large.

Introduction

Soil subsidence related to agricultural drainage of organically rich soils occurs throughout the world (Stephens *et al.*, 1984). The principal source of subsidence is generally believed to be oxidation of soil carbon. Hence, subsidence measurements are usually used as surrogates for the contribution of drained organic soils to atmospheric carbon dioxide (Armentano, 1980). World-wide annual input of atmospheric carbon due to agricultural drainage of organic soils has been estimated to be as much as 6% of that produced by fossil fuel combustion (Armentano, 1980; Tans *et al.*, 1990). However, such processes as mechanical compaction, wind erosion, anaerobic decomposition, and dissolution of carbon have been cited as significant contributors to soil subsidence. Because of these other influences, estimation of CO_2 flux from subsidence history has significant uncertainty. Also, estimates of carbon loss have been based on time-averaged subsidence rates. If subsidence and associated carbon loss vary significantly over time, these time-averaged estimates can be in error.

Previous studies have correlated field measured subsidence rates inferred from periodic leveling surveys in the Florida Everglades with laboratory measurements of gaseous CO_2 flux (Stephens and Stewart, 1976). In this paper, we examine subsidence and CO_2 flux in the San Joaquin-Sacramento Delta using a field based approach. We use periodic leveling surveys, field measurements of gaseous carbon fluxes, and continuous point measurements of land elevation in the Delta. This field based approach gives us direct comparison of subsidence and carbon loss. The Delta is a prime region to examine the relationship between CO_2 fluxes and subsidence. The region has been drained for agriculture for over a century and has historical rates of subsidence that are among the highest observed in the world (Stephens *et al.*, 1984; Weir, 1950). The objectives of the study are to examine the use of subsidence rates to infer CO_2 flux to the atmosphere and to examine the temporal variation of carbon flux.

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Historical Subsidence Rates

The San Joaquin-Sacramento Delta (Figure 1) is 1 x 10^5 ha in area and consists of tidal marsh land that was drained for agriculture beginning in 1867 (Gilbert, 1917; Thompson, 1957; Atwater and Belknap, 1980). The Delta assumed its current form by the 1930s when drainage of 100 islands and tracts and construction of about 2250 levees were completed. Water levels on the islands generally are now maintained 1 to 2 m below the land surface by a network of drainage ditches.

Historical rates of subsidence can be obtained from periodic leveling surveys over the time period 1922-1981 along Bacon and Mildred Islands and Lower Jones Tract (Figure 2a). The leveling lines that cross the three islands are collectively referred to as the Weir transect (Weir, 1950; Broadbent, 1960). Twenty-one complete surveys following the route shown in Figure 2a were conducted between 1922 and 1981. The eighteen surveys for which closure error information is available show that closure differences range from 1.2 to 12 cm. Assuming that this closure error is random and spread equally across the 12 km of the transect, the leveling error is small relative to the rate of subsidence.

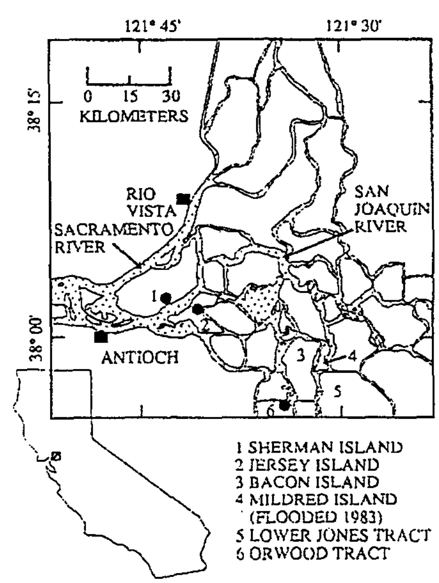

Fig. 1. Location of San Joaquin-Sacramento Delta and its associated islands and tracts. Location of subsidence and carbon flux measurements are denoted by solid circles.

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Mean annual elevation for the three islands along the transect is shown in Figure 2b. To obtain elevation histories, the mean elevation of each island was calculated for every repeat survey, removing survey points that were taken on mineral soil. The elevation histories can be fit with high correlation coefficients assuming that elevation is a linear or logarithmic function of time. However, the residual values for the logarithmic model are normally distributed around zero. In contrast, the residuals for the linear model are negatively skewed and not normally distributed. Assuming that subsidence is caused primarily by soil oxidation, the declining rates of soil subsidence in these drained lands is similar to declining rates of organic matter loss in upland soils subject to cultivation (Dormaar, 1979).

Median annual subsidence rates were 5.1 cm/yr on Lower Jones Tract and 7.6 cm/yr on Mildred and Bacon Islands. In contrast to these time-averaged rates, the logarithmic model estimates and predicts subsidence rates in 1980 and 1990 of 4.2 and 3.6 cm/yr on Bacon Island, 4.1 and 3.6 cm/yr on Mildred Island and 3.1 and 2.7 cm/yr on Lower Jones Tract. Since the time-averaged rates are higher, any estimates of current atmospheric CO_2 input based on time-averaged subsidence rates will also be high. It should be noted that the rates of historical subsidence in the central Delta are higher than those on Sherman Island in the western Delta (Rojstaczer *et al.*, submitted to *Global Biogeochemical Cycles).* The difference can be at least partly attributed to spatial variations in soil organic content and indicates that historical rates of subsidence in the Delta as a whole are less than that observed along the Weir transect.

Contemporary Subsidence Rates and Carbon Flux

Contemporary rates of elevation loss were measured continuously from 3/90-6/91 on Sherman and Jersey Island and Orwood Tract. Elevation changes were monitored with a displacement transducer attached to a tripod with legs anchored 3-7 m below the base of the organic soil. The transducer arm was weighted with a 0.6 cm thick aluminum plate that rested on the land surface. The displacement transducer was sampled hourly with a computer equipped with an analog to digital converter. Water table depths were measured with pressure transducers submerged in shallow (less than 3 m depth), 5.1 cm diameter wells in the center of the tripod. The contemporary elevation data indicate that elevation consists of an elastic component related to the height of the water table (Figure 3) and a long term permanent decline. The elastic component has been noted in other studies and reflects the buoyant effect of groundwater (Schothorst, 1977). Elevation changes not related to groundwater level can be obtained by comparing elevations at times when the water table was at the same level. The rates of permanent decline at the three sites are 1.0-1.5 cm/yr.

Periodic field determination of gaseous carbon flux (Figure 4) indicates that much of the measured subsidence over the time period 5/90-6/91 can be explained by carbon oxidation. Gaseous carbon fluxes were determined at each elevation monitoring site and four locations surrounding each elevation monitoring site using closed chamber techniques (Rolston, 1986). Carbon fluxes have a strong seasonal character that can be explained by soil temperature (Deverel *et al.*, submitted to *Global Biogeochemical Cycles*). The measured fluxes are a mixture of CO_2 derived from plant-root respiration and biochemical oxidation of organic matter. $^{13}C/^{12}C$ isotopic ratios (expressed as delta values) and ^{14}C concentrations were determined from gas samples collected in a chamber placed in the fields in June and November 1990 (Table 1). The $\delta^{13}C$ values range from -16.6 to -21.9‰. ^{14}C values range from 86.6 to 106.1% modern carbon.

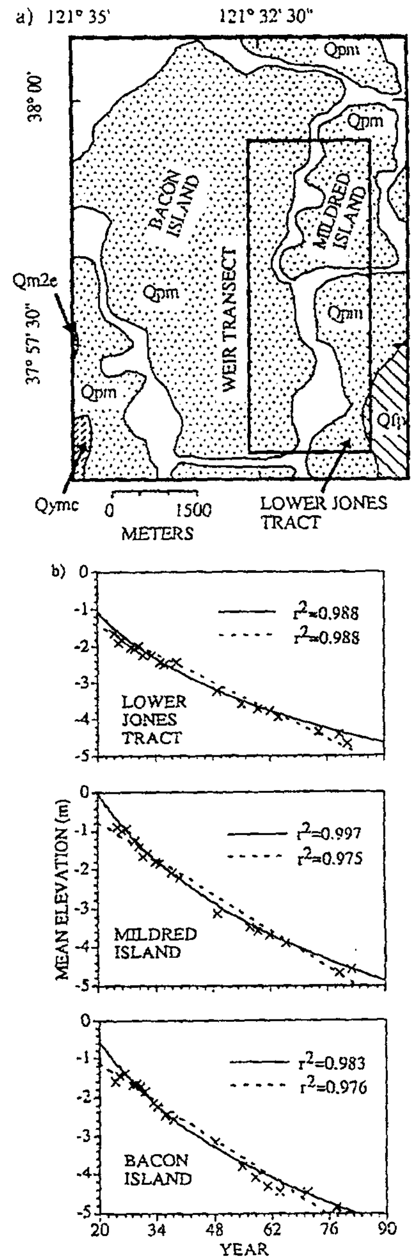

Fig. 2. (a) Location of periodic leveling survey. Rectangle denotes path of survey (Weir transect). Qpm and Qfp denote Holocene tidal wetland peat and alluvial flood plain deposits, respectively. Qymc denotes Holocene and upper Pleistocene alluvium. Qm2e denotes upper Pleistocene eolian deposits. Contact between deposits may be in error by more than 150 m. Geologic data from Atwater (1982). (b) Mean elevation history for each island or tract along survey.

Samples collected in November 1990 on Sherman Island at a site where there was no vegetation indicate that gas evolving from organic-matter oxidation has a $\delta^{13}C$ value of about -22‰. Bermuda grass (*Cynodon dactylon)* is the primary vegetation on Sherman and Jersey Island. CO_2 derived from its root respiration has a $\delta^{13}C$ value of about -13‰ (Deines, 1980). Using the end member values of -13‰ and -22‰ we estimate that 40% and 44% of the CO_2 in the samples at

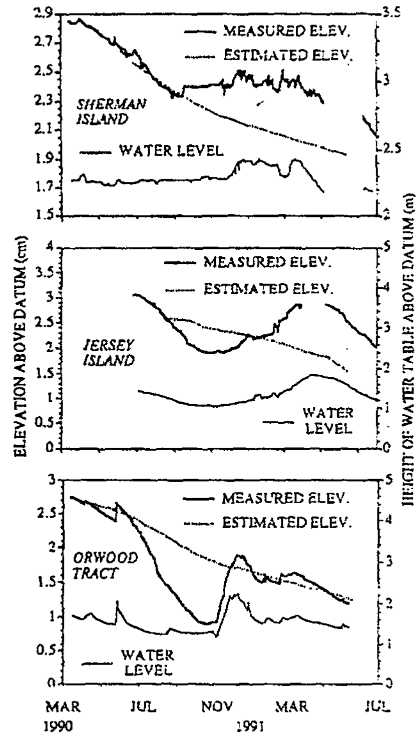

Fig. 3. Water table height, measured elevation loss, and elevation loss predicted from gaseous carbon flux at each site, 3/90-6/91.

Sherman and Jersey Island respectively were derived from organic matter oxidation. These percentages are comparable to that found in upland soils (Raich and Schlesinger, 1992).

Samples collected at the Orwood Tract site were collected in an asparagus field (*Asparagus officinalis*) which has a $\delta^{13}C$ value of about -26‰ (Deines, 1980). Because of the similarity of $\delta^{13}C$ values from peat oxidation and asparagus-root respiration, it is difficult to distinguish between the two sources of CO_2 using ^{13}C data. However the CO_2 sample in November was about 92% modern carbon, close to the value of 93.1% modern carbon for the Sherman Island sample. The CO_2 probably was derived primarily from organic-soil oxidation.

We compared measured elevation loss with that resulting from organic soil oxidation. We assumed that 50% of the measured CO_2 flux was due to organic-soil oxidation during

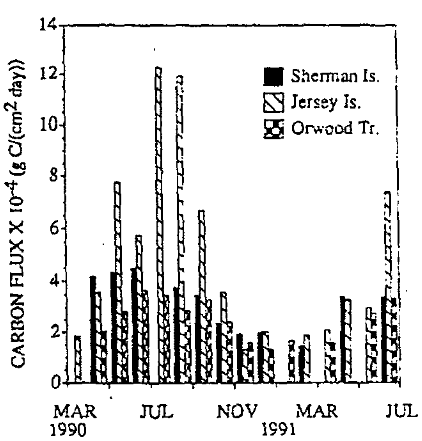

Fig. 4. Mean carbon flux at each site, 3/90-6/91.

TABLE 1. Delta ^{13}C values and percentage of modern carbon in CO_2 samples (E denotes measurement at extensometer site, and F denotes measurement in the surrounding field)

Site	Date	$\delta^{13}C$ (‰)	Modern C (%)	Vegetation
Jersey				
F	06-27-90	-16.6	--	Bermuda grass
F	11-12-90	-21.1	87.1	None
F	11-12-90	-21.3	86.6	None
E	06-27-90	-17.3	--	Bermuda grass
E	11-12-90	-17.4	97.9	Bermuda grass
Orwood				
F	11-12-90	-20.1	92.3	Asparagus
F	11-12-90	-20.3	91.1	Asparagus
Sherman				
E	11-12-90	-17.8	106.1	Bermuda grass
F	11-12-90	-19.1	102.7	Bermuda grass

February through November when the Bermuda grass was growing and 100% of the measured flux in December and January. We assumed that 1/2 of the organic matter was carbon (Broadbent, 1960) and used average bulk densities and organic contents of soil at each site to relate carbon loss to elevation loss (Table 2). The estimated oxidation related elevation loss is shown in Figure 3. At Sherman Island, estimated subsidence agrees with subsidence measured until September 1990. The estimated elevation loss is probably greater than that measured during the winter and spring months because of a rising water table. At Jersey Island, subsidence calculated from CO_2 fluxes agrees best with actual subsidence from late July to February. Calculated subsidence rates in the early spring of 1991 may be greater than measured values because of the overestimation of the percentage of carbon flux due to organic-soil oxidation. At Orwood Tract, measured net subsidence corresponds closely to net subsidence calculated from CO_2 fluxes over the period of measurement.

Conclusions

The contemporary measurements of soil subsidence rates and gaseous carbon flux due to oxidation are probably too low to be representative of each island. The measurements were made along the edge of the islands. Historical leveling surveys indicate that subsidence rates are as much as a factor of two greater in the island center than the island edge (Rojstaczer *et al.*, submitted to *Global Biogeochemical Cycles*). Current average rates of elevation loss for these islands are likely to be about 2 cm/yr. Given the values for bulk density and percentage organic matter in Table 2, a subsidence rate of 2 cm/yr corresponds to a carbon flux of 5 x 10^{-4} gm cm^{-2}sec^{-1}.

TABLE 2. Average organic content and bulk density of samples taken near the elevation monitoring sites

Site	Organic Matter (%)	Bulk Density (gm/cm^3)
Sherman Island	28.0	0.85
Jersey Island	20.0	0.96
Orwood Tract	24.4	0.85

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This value for carbon flux would be consistent with the measured atmospheric CO_2 flux if one assumes that CO_2 fluxes are higher in the island center. Integrated over the entire Delta (1×10^5 ha), the carbon flux is 2×10^{12} gm/yr, a factor of 3-4 less than earlier estimates (Stephens *et al.*, 1984; Armentano, 1980) which indicates that oxidation of soil organic matter in the Delta has a smaller impact on the global carbon cycle than previously thought. The lower values presented here reflect the declining rate of subsidence. The initial rapid CO_2 fluxes caused by agricultural drainage in the Delta are similar to that caused by agricultural expansion into virgin areas at the turn of the century (Wilson, 1978).

It is likely that the earlier estimates of losses of carbon to the atmosphere were appropriate for the Delta early in its history as a drained agricultural land. Alternatively, carbon flux rates have been constant over time, but the impact of carbon loss on subsidence has decreased due to more efficient packing of sediment. This latter hypothesis is unlikely based on our contemporary subsidence measurements. The correspondence between contemporary subsidence and carbon loss indicates that the bulk density changes associated with subsidence are largely due to a decrease in the percentage of carbon, rather than a collapse of pore space. Carbon dissolution by groundwater appears to be a small component of subsidence as does the influence of groundwater and natural gas withdrawal (Rojstaczer *et al.*, 1991; Rojstaczer *et al.*, submitted to *Global Biogeochemical Cycles*)

The historical subsidence data shown in Figure 3 indicate that the time-averaged values previously used to estimate carbon fluxes were appropriate for the 1930s in the central Delta. Over the following decades, subsidence and carbon inputs into the atmosphere have declined significantly. Changes in farming practice (crop type grown and burning frequency of fields) over the time period 1922-1981 had a small influence, if any, on subsidence rates (Rojstaczer *et al.*, submitted to *Global Biogeochemical Cycles*). The decline in subsidence rate is probably due to the decreasing amount of readily decomposable carbon in the organic content of the soil.

Previous estimates of world-wide annual input of atmospheric carbon due to agricultural drainage of organic soils have been based upon time-averaged subsidence rates in regions undergoing carbon oxidation such as the Delta and the Florida Everglades. Our analysis of Delta subsidence and carbon flux would suggest that these estimates are too large. They ignore the tendency for agricultural drainage to release smaller amounts of carbon to the atmosphere over time. Estimates of global carbon effects due to agricultural drainage should take into account the time history of subsidence in each region.

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References

Armentano, R.V., Drainage of organic soil as a factor in the world carbon cycle, *Bioscience*, 30, 825-830, 1980.

Atwater, B.F., Geologic maps of the Sacramento-San Joaquin Delta, California, *U.S. Geol. Surv. Map MF-1401*, 1982.

Atwater, B.F., and D.F. Belknap, Tidal-wetland deposits of the Sacramento-San Joaquin Delta, California, in *Quaternary Depositional Environments of the Pacific Coast: Society of Economic Paleontologists and Mineralogists, Pacific Coast Paleogeography Symposium 4*, edited by M. Field, pp. 89-103, 1980.

Broadbent, F.E., Factors influencing the decomposition of organic soils of the California delta, *Hilgardia*, 29, 587-612, 1960.

Deines, P., The isotopic composition of reduced organic carbon, in *Handbook of Environmental Isotope Geochemistry*, edited by J.C. Fontes, pp. 329-406, Elsevier, Amsterdam, 1980.

Dormaar, J.F., Organic matter characteristics of undisturbed and cultivated chernozemic and solonetzic A horizons, *Canadian J. Soil Sci.*, 59, 349-356, 1979.

Gilbert, G.K., Hydraulic-mining debris in the Sierra Nevada, *U.S. Geol. Surv. Prof. Pap. 105*, 154p., 1917.

Raich, J.W., and W.H. Schlesinger, The global carbon dioxide flux in soil respiration and its relationship to vegetation and climate, *Tellus*, 44B, 81-99, 1992.

Rojstaczer, S.A., R.E. Hamon, S.J. Deverel, and C.A. Massey, Evaluation of selected data to assess the causes of subsidence in the Sacramento-San Joaquin Delta, California, *U.S. Geol. Surv. Open-File Rep. 91-193*, 16p., 1991.

Rolston, D.E., Gas flux, in *Methods of Soil Analysis. Part 1. Agron. Monograph 9*, edited by A. Klute, pp. 1103-1119, Am. Soc. Agron. & Soil Science Soc. Am., Madison, WI, 1986.

Schothorst, C.J., Subsidence of low moor peat soil in the western Netherlands, in *Institute of Land and Water Management Research Technical Bulletin 112*, Wageningen, Netherlands, pp. 265-291, 1977.

Stephens, J.C., L.H. Allen, Jr., and E. Chen, Organic soil subsidence, in *Man-Induced Land Subsidence. Reviews in Engineering Geology 6*, edited by T.L. Holzer, pp. 107-122, Geological Society of America, Boulder, CO, 1984.

Stephens, J.C., and E.H. Stewart, Effect of climate on organic soil subsidence, *Int. Assoc. of Hyd. Sci.*, 121, 649-655, 1976.

Tans, P.P., I.Y. Fung, and Y. Takahashi, Observational constraints on the global atmospheric CO_2 budget, *Science*, 247, 1431-1438, 1990.

Thompson, J., The settlement geography of the Sacramento-San Joaquin Delta, California, Ph.D. thesis, Stanford University, 551p., 1957.

Weir, W.W., Subsidence of peat lands of the San Joaquin-Sacramento Delta, California, *Hilgardia*, 20, 37-56, 1950.

Wilson, A.T., Pioneer agriculture explosion and CO_2 levels in the atmosphere, *Nature*, 273, 40-41, 1978.

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