



Production of dissolved organic carbon (DOC) and trihalomethane (THM) precursor from peat soils

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Abstract

Water passing through the Sacramento-San Joaquin Delta contains elevated concentrations of dissolved organic carbon (DOC) and trihalomethane (THM) precursor relative to upstream waters from the Sacramento River and the San Joaquin River. Drainage from agricultural peat soils has been identified as one of the major sources of DOC and THM precursor. A series of controlled laboratory experiments were conducted to evaluate abiotic and biotic effects on the quantity and the nature of DOC and THM precursors produced from oxidized surface and reduced subsurface soils in the Delta. For abiotic effects, DOC was extracted from both soils with synthetic solutions containing a range of salinity (0–4 dS/m) and sodicity (0 to ∞). The results showed that an increase in salinity significantly decreased the concentration of DOC in the soil-water from both soils but increased its aromaticity, as indicated by specific ultraviolet absorbance at 254 nm (SUVA). For biotic effects, peat soils were incubated over a range of temperatures (10°C, 20°C and 30°C) and soil moisture contents (0.3–10 g water/g soil). After 8 weeks of incubation, only extracted DOC from flooded conditions and flooded and non-flooded cycles showed an increase in DOC. These findings indicate that neither salinity nor sodicity is the major factor for DOC production, but both can affect the solubility and mobility of DOC in the Delta soils. We believe wetting processes in oxidized peat soils produce significant amounts of DOC found in agricultural drainage discharged into the Delta waters.

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1. Introduction

The Sacramento-San Joaquin Delta (Fig. 1), hereafter referred to as the Delta, supplies drinking water for over 23 million people in California, USA. There is a significant increase in dissolved organic carbon (DOC) when water passes through the Delta. Water from the Sacramento River has an average of 2 mg/L total organic carbon (TOC) but it can often exceed 4 mg/L TOC or even reach 8 mg/L during storm events at the diversion site for the California Aqueduct, which delivers water to Southern California [1]. Not only does

DOC cause color and odor in water, but it also is a precursor of trihalomethane (THM). THM is formed when dissolved organic matter reacts with chlorine during water treatment. THM is of concern because of its potential carcinogenic and mutagenic properties [2]. It was estimated that agricultural drainage from Delta islands contributes about 20–50% of the DOC that leads to the formation of THM precursors in chlorinated Delta waters [3,4]. The decomposition of the Delta peat soils is the principal source of DOC in drainage water [3].

The Delta region originally was a large tidal marsh area. Thick organic soil was formed as bulrushes (*Kirpus* spp.) and reeds (*Phragmites* spp.) were covered by sediment from river flows and tidal action [5]. These inter-tidal organic deposits began to accumulate in

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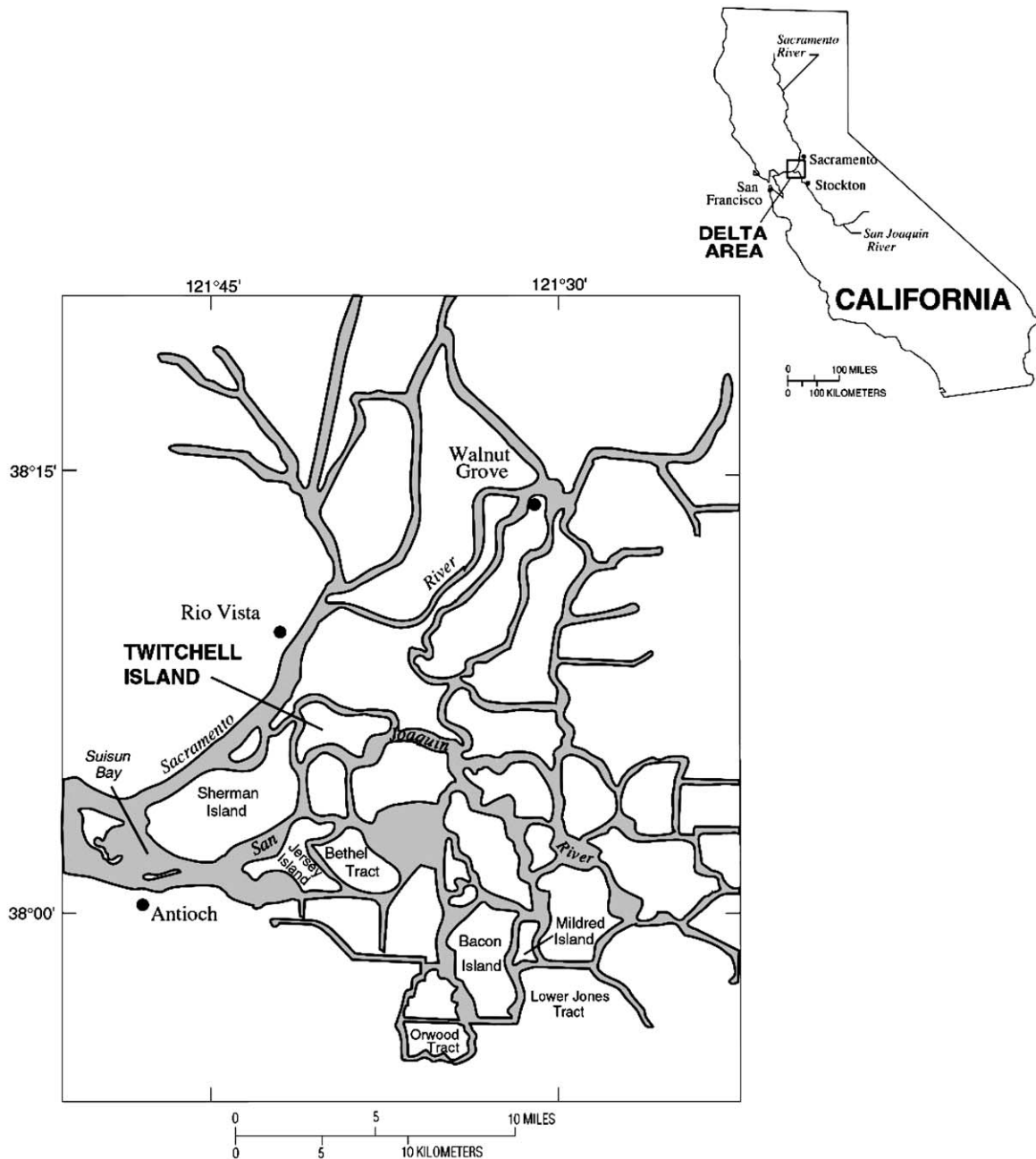


Fig. 1. Location of Sacramento-San Joaquin Delta and Twitchell Island.

the Delta about 7000 years ago [6]. Peat deposits average 5 m in depth, with an increase in depth toward the western apex of the Delta. In some areas, these organic soils are up to 18 m deep and consist of 50–80% organic matter [4]. Beginning in the late 1850s, levees were constructed to form islands and the lands were drained for agricultural production. Currently, most peat lands in the Delta are devoted to corn,

tomatoes and other field crops, and these cultivated peat lands are saturated twice a year, during summer and winter [4]. Summer saturation occurs typically from May–August using special sub-irrigation methods. The winter saturation occurs from December to January and is caused by winter rainfall and the flooding of croplands by landowners to leach out salts accumulated in the soils from summer irrigation. The

croplands are flooded for one to two months and then drained [4].

The volume and quality of drain water discharged into the Delta's channels correlate with the seasonal farming activities [4]. Current factors such as summer intensive irrigation, winter precipitation, and winter flooding can change soil-water composition and soil aeration and eventually affect the chemistry and microbial processes in the soils. Soil salinity and sodicity increase in summer due to rapid evaporation of soil-waters, whereas soil salinity and sodicity decrease in winter due to salt leaching. Tanji and Doneen [7] noted that the color of leachates from the peat soils of the Delta vary with soil water salinity. They are straw-colored at elevated salinity, but change to grayish-black and contain high concentrations of dispersed organic colloidal matter at lower salinity. Changes in soil salinity can potentially affect the structure of soil organic matter (SOM) and possibly change the concentration of DOC in the drainage water. In addition to salinity, the sodicity or sodium adsorption ratio (SAR) of soil water may play an important role in the DOC concentration in drainage waters. SAR is defined as $[\text{Na}^+]/([\text{Ca}^{2+}] + [\text{Mg}^{2+}])^{0.5}$, with ion concentrations in mM/L. Not all cations have the same effectiveness with respect to DOC coagulation. Romkens and Dolfin [8] have shown that the divalent calcium ions effectively flocculate up to 50% of the DOC originally present in the water samples. These results suggest that sodicity could play an important role in the mobility of different dissolved organic matter fractions, which may affect leaching of THM precursors in the soil environment.

In addition to changing the soil chemistry, the current agricultural practices and weather create seasonal and short-term flooded and non-flooded cycles in the field, which could affect soil aeration and create anaerobic or reducing conditions in the soil environment. Sihombing et al. [9] showed that the local oxidizing/reducing environment greatly alters the gross structural group content of the SOM. Hogg et al. [10] also suggested that surface peat soils have already been exposed to long periods of aerobic decay and may be highly resistant to further decay. However, the flooded and non-flooded cycles or aerobic–anaerobic cycles in the fields could promote a diversity of microorganisms and provide different pathways to decompose the refractory peat materials throughout the soil profile. Thus, soil moisture content and flooded and non-flooded cycles may affect both the mechanism and the rate of decomposition of peat soil, and may also affect the quantity as well as the nature of DOC leaching from the cultivated peat land.

Most peat lands have relatively shallow groundwater and range 1–2 m in depth in the Delta. Soils above and below the water table significantly differ and they are characterized as oxidized and reduced peat soils, respectively. A 2-year field study conducted by the US

Geological Survey (USGS) [11] indicated that the reduced soil layer contained slightly higher concentrations of DOC and greater amounts of humic material than soil waters from the oxidized soil layer.

However, the specific processes by which these high concentrations of DOC are produced are not known. In order to identify these processes, we conducted a series of controlled laboratory experiments. We examined abiotic and biotic effects independently in upper oxidized soil and lower reduced soils. For the abiotic effect, we evaluated the DOC leaching process due to variations in the salinity and sodicity of summer irrigation and winter salt leaching management. For the biotic effect, the microbial activity was evaluated due to variations in temperature and moisture content on DOC productions are evaluated.

2. Materials and experimental methods

2.1. Site description and soil

Soil samples from an agricultural field on Twitchell Island in the west-central Delta (Fig. 1) were collected for this study. The field was chosen to represent typical land-use practices in the Delta. Much of Twitchell Island is composed of highly organic soils under agricultural cultivation. The soil at the sampling site is classified as a Rindge muck, with oxidized, well-decomposed peat dominating from the surface to about 0.5 m below the land surface, and reduced, fibrous peat dominating below about 1–1.5 m [11]. Soil samples were collected from two soil depths, 0–0.5 and 2.5–3 m from the surface to represent upper oxidized soil and lower reduced soil, respectively.

2.2. Soil sampling and soil characterization

The oxidized peat soil was collected with a spade, air-dried and then sieved through a 2 mm sieve. The soil was stored at 4°C in a dark room in plastic bags until further use. For the reduced peat soil, a 3-m deep trench was dug to reach the deeper reduced layer. Fibrous peat samples were taken from the walls of the trench and promptly put into plastic bags and sealed with N₂ to preserve their reduced condition, and then stored in ice chests for transport to the laboratory. Just before experimentation, the reduced soil was sieved through a 9.5 mm sieve in a glove bag filled with N₂. The soil moisture content was determined by freeze drying as well as drying in a 55°C oven for 48 h. This temperature and duration is to avoid excessive oxidation [12]. The gravimetric soil moisture content (θ_g) of the oxidized peat soil was about 24% on a mass basis, and the reduced peat soil about 500%. Extracts from saturated soil pastes were used to determine the soil properties of

both the oxidized and reduced peat soils [13]. The drawback of this experimental procedure was that because it required that the soil be saturated with water and left overnight at room temperature before extraction, reduced conditions could develop in saturated oxidized soil. The Eh value of the saturated paste from the reduced peat soil was anomalously higher than that for the oxidized peat soil, 128 millivolts (mV) compared to 55 mV, respectively. Also, about 5 g of soil (oven dried at 55°C for 48 h) was incinerated at 450°C for 12 h to determine SOM. Table 1 presents the physical and chemical properties of the oxidized and reduced soils.

2.3. Abiotic effects—successive extractions

The abiotic effects of salinity and sodicity on both the oxidized and reduced peat soils were determined by five successive extractions of 1:10 (w:w) soil-to-solution slurry. The synthesized solutions used in the experiments were prepared from reagent grade CaCl_2 and NaCl dissolved in distilled deionized water (DDW). The electrolyte concentrations and sodicity of the test solutions used were in the range of soil waters present on Twitchell Island [11]. For the salinity experiment, the specific conductance (K) of the solutions was 0.0 (DDW), 0.5, 1.0, and 4.0 dS/m with a SAR fixed at 5. The SAR in the test solution was defined as $[\text{Na}]/[\text{Ca}]^{0.5}$, with ion concentrations in mM/L. The DDW had a K less than 0.001 dS/m. For the sodicity experiment, the salinity of the solutions was fixed at 4 dS/m and the SAR

was 0, 5 and ∞ . The soil-solution mixture was shaken for 2 h at 4°C. The purpose of the cold environment was to minimize microbial activity during the shaking periods. Then, the samples were centrifuged for 20 min at 16,270g relative centrifugal force at 4°C. The supernatants were collected and filtered through 1.2 μm glass fiber filter (Fisher G4) and then through 0.45 μm membrane filters (Supor-450). The extracted soil residues were retained, another aliquot of the same solution was added at a 1:10 soil-to-solution ratio, and then the mixtures was shaken again before the subsequent extraction. Five successive extractions for each solution were conducted. To minimize the effects of oxidation in the reduced peat soil treatments, all the solutions were bubbled with N_2 for not less than 5 min before the test solutions were added to the reduced soils. The dissolved oxygen (DO), measured with an YSI model 54 DO meter, was less than 0.5 mg/L.

2.4. Biotic effects—incubation experiment

Before the incubation experiments, the oxidized peat soil was air-dried, sieved through a 2-mm sieve, and washed with a synthesized carbon-free solution ($K = 0.5$ dS/m and SAR = 5) to remove excess salt and DOC. This additional procedure was necessary because our preliminary study showed that the background DOC in the surface soil was so high that the increase of DOC from a 2-month incubation experiment was masked by initial values, and biotic effects from the

Table 1
Relevant properties of the oxidized and reduced peat soils (mean of 4 samples)

Description	Oxidized soil (0.5 m depth)	Reduced soil (2.5–3 m depth)
Saturation water percentage, g/100 g	156 \pm 2	871 \pm 43
pH of saturated soil extract	6.6 \pm 0.1	6.7 \pm 0.2
Eh of saturated soil extract, mV	55 \pm 30	128 \pm 59
K of saturated soil extract, dS/m	4.44 \pm 0.09	0.59 \pm 0.05
Soil organic matter (SOM), % (w/w)	49.9 \pm 0.8	39.4 \pm 3.0
<i>Saturation soil extract analyses</i>		
Total organic carbon (TOC) in mg/L	296 \pm 7	21 \pm 3
Inorganic carbon (IC) in mg/L	19 \pm 7	2.3 \pm 0.3
Total carbon (TC) in mg/L	315 \pm 9	23.5 \pm 2.9
Na in mg/L	505 \pm 20	63.4 \pm 7.3
Ca in mg/L	233 \pm 7	14.7 \pm 1.6
Mg in mg/L	175 \pm 3	12.1 \pm 1.8
K in mg/L	12.8 \pm 0.2	6.4 \pm 0.4
Mn in mg/L	2.45 \pm 0.17	0.27 \pm 0.02
NH_4 in mg/L	8.96 \pm 0.80	6.4 \pm 1.0
Cl in mg/L	1092 \pm 12	167 \pm 11
SO_4 in mg/L	897 \pm 23	21.9 \pm 4.5
Total cations in meq/L	48.9	5.02
Total anions in meq/L	49.4	5.16
Sodium adsorption ration (SAR) in (mM/L) ^{0.5}	6.1	3.0

$$\text{SAR} = [\text{Na}]/([\text{Ca}] + [\text{Mg}])^{0.5}.$$

experiments were difficult to evaluate. In addition, we were interested in the DOC production from the peat soils so DOC from the crop debris needed to be removed. This procedure is analogous to salt leaching, which is a common practice in the Delta. In contrast, the reduced soil was not washed because the concentration of DOC was much lower and it was desirable to maintain its reduced status and minimize any changes in redox status.

Table 2 lists the incubation conditions. In each treatment, 35 g (dry weight) of oxidized peat soil or 15 g (dry weight) of reduced peat soil was placed in a 1-L wide-mouth glass Mason jars. Different masses of oxidized peat soil and reduced peat soil were used in the incubation experiment because of the lower bulk density of the reduced peat soil. Water with $K = 0.5$ dS/m and SAR=5 was sprinkled onto the soils to obtain the desired moisture content. There were three replicates for each treatment and all jars were placed in constant-temperature chambers. The Mason jar for DOC extraction was covered by a lid with a 2-mm opening for gas exchange. All treatments were incubated for 8 weeks. At the end of the incubation, 15 g of soil (dry weight) was collected and water with $K = 0.5$ dS/m and SAR=5 was added to form a 1:10 (w:w) soil-to-water suspension and the mixture was shaken at 4°C for 4 h. The same extraction procedure as in abiotic experiments was applied here except that the soils were extracted one time, instead of five.

2.5. Analysis

All the extracted waters were analyzed for DOC, UVA, pH and K . The concentration of DOC was determined by UV-promoted persulfate oxidation, and a DOHRMANN DC-180 carbon analyzer was used. UVA was determined by a diode array spectrophotometer HP8452A. A Beckman $\Phi 71$ pH meter and a YSI model 32 conductance meter were used to determine the pH and K of the soil solutions, respectively. Selected

samples were further characterized by XAD-fractionation and THM formation potential (THMFP). In the XAD-fractionation [14], 20 mL capacity columns were used and these column-processed sample volumes of 1 L with a DOC concentration of not greater than 20 mg/L for maximum adsorption efficiency. The samples were acidified to pH 2 by the addition of 12.1 N HCl. After acidification, the samples were run on the XAD-8 column, and the effluent was collected in an Erlenmeyer flask. The XAD-8 effluent was then run through the XAD-4 column and the XAD-4 effluent was collected in an Erlenmeyer flask. These samples were run through both columns at a rate of 4 mL/min. After all the samples were run through the columns, each column was separately back eluted with 100 mL of 0.1 N NaOH at a rate of 2 mL/min. The eluates were collected in volumetric flasks and acidified to pH 2 with 12.1 N HCl. The eluate from XAD-8 is defined as hydrophobic acid (HPOA) and the eluate from XAD-4 is defined as hydrophilic acid (HPIA). The hydrophobic neutral (HPON) and hydrophilic neutral (HPIN) are those compounds that adsorb onto the XAD-8 and XAD-4 resins, respectively, but are not dissolved during the back elution with NaOH. The non-adsorbed hydrophilic acid (NA-HPIA) is the carbon in the XAD-4 effluent.

The reactivity-based test THMFP method was used in this study and each sample was determined using a modified version of method 5710B described in [27]. Briefly, samples were chlorinated with a freshly prepared NaOCl/H₃BO₃ buffer with pH 8.3 ± 0.1 . The chlorine dosage was based on the inorganic and organic demand according to the formula $[Cl_2] = (3 \times [DOC]) + (7.6 \times [NH_3])$ [15]. Ammonia concentrations were determined using a HACH kit according to the method 8038 of the HACH Water Analysis Book [16]. Samples were stored in a 72-mL serum vial and sealed using a Teflon-faced septa without leaving headspace. The bottles were then incubated for 7 days at 20°C in a temperature-controlled incubator. Then, 0.5 mL of 8% sodium thiosulfate solution was used to

Table 2
Incubation conditions for the biotic effects

Temperature			Soil used	Water conditions
10°C	20°C	30°C		
Water content (θ_g) 0.3	0.3	0.3	Oxidized soil	Non-flooded
	0.7		Oxidized soil	
10	5		Oxidized soil	Flooded
	10	10	Reduced soil	
	0.3–5 4–10		Oxidized soil Reduced soil	Flooded & non-flooded cycles

quench residual chlorine after 7 days of incubation. Quantification of THM was accomplished using a Hewlett Packard 5890 II gas chromatograph fitted with an auto injector, a capillary split-splitless inlet, and a Nickle⁶³ electron capture detector.

3. Results and discussion

3.1. Upper oxidized peat soils vs. lower reduced peat soils

Table 1 presents physical and chemical properties of both the oxidized (0–0.5 m) and reduced (2.5–3 m) peaty soils. First, differences are noted for these two soil samples. The percentage of water for saturation for the reduced soil was exceedingly high (871 g water/100 g soil), reflecting the high water holding capacity of the undecomposed fibrous peat, while that of the oxidized soil was only 156 g water/100 g soil. Second, the surface soil was saline from sub-irrigation and the sub-surface soil was non-saline. The *K* of the saturated soil extract of the oxidized surface soil was 4 dS/m and for the reduced subsoil it was 0.6 dS/m. The water-soluble constituents in the upper oxidized soil were dominated by Na^+ , Cl^- and SO_4^{2-} , and the lower reduced soil by mixed cations and Cl^- . The SAR of the surface soil was twice as large as that of the reduced soil. Third, SOM contents were similar in the two soils; however, the DOC in the saturation extract was 14 times greater in the oxidized than in the reduced soil. In addition to the byproducts of the microbial degradation of peat soils, the excessive DOC in the oxidized soils was possibly from the crop debris [17].

Using XAD-8 and XAD-4 resins, extracted DOC from the oxidized and reduced peat soils was fractionated into 5 fractions: HPOA, HPIA, HPON, HPIN, and NA-HPIA. Fig. 2 shows that the XAD-8 and XAD-4 resins absorbed and removed approximately 60% of

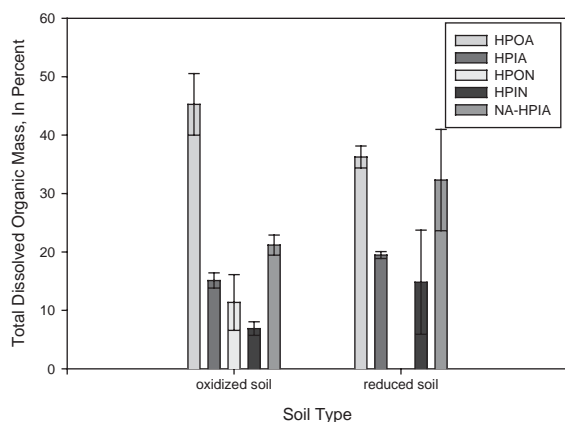


Fig. 2. Fractionation of DOC from oxidized and reduced peat soils.

the DOC (sum of HPOA, HPIA, HPON, and HPIN) from both the oxidized and reduced soils. For the NA-HPIA, approximately 21% of the extracted DOC from the oxidized soils and 32% from the reduced was not absorbed and passed through both columns. Among the fractions, the HPOA, which was the major fraction, accounted for 45% and 38% of DOC in the oxidized soil and reduced soil samples, respectively. In spite of this similar proportion, the carbon-normalized THMFP (Also called specific THMFP (STHMFP), which is defined as millimoles (mmol) of THM formed per mole (mol) of DOC) of the HPOA from the oxidized soil was twice as high as that of the HPOA from the reduced soil (Fig. 3).

3.2. Abiotic effects—salinity and sodicity

Both oxidized and reduced peat soils were successively extracted five times with electrolyte solutions of various levels of *K* and SAR. The results are summarized in

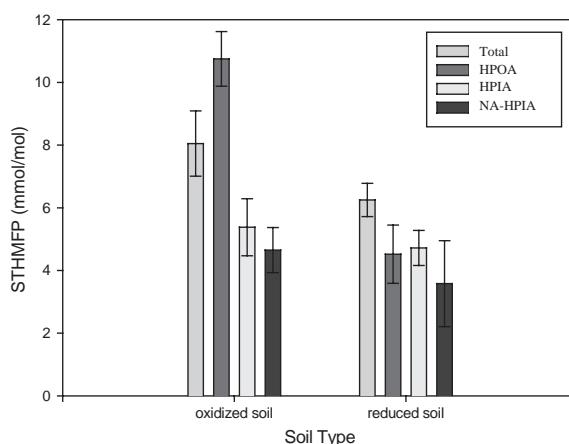


Fig. 3. STHMFP of each DOC fraction from oxidized and reduced peat soils.

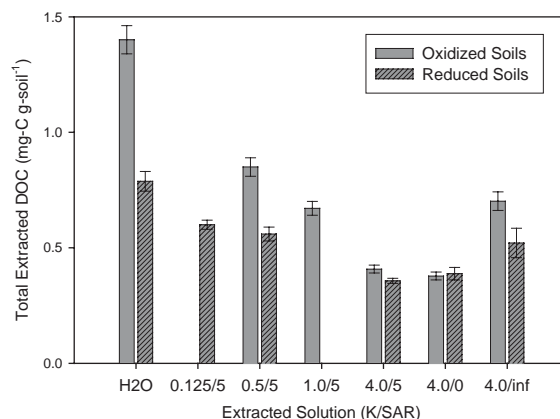


Fig. 4. Salinity and sodicity effects on DOC extraction.

Fig. 4. We noted that the concentrations of DOC extracted from the oxidized peat soils were higher than those from the reduced peat soils at the same electrolyte concentration K . An increase in K resulted in significantly less carbon extracted ($\alpha = 0.05$) for both the oxidized and reduced soils. The highest saline solutions ($K = 4 \text{ dS/m}$) in the experiments withdrew approximately 0.4 mg C/g soil in both the oxidized and reduced soils, but the solutions with lower K ($0.125 \text{ dS/m} \leq K \leq 1 \text{ dS/m}$) extracted approximately $0.7\text{--}0.9 \text{ mg C/g soil}$ and 0.6 mg C/g soil in oxidized and reduced soils, respectively. The DDW treatment, $K < 0.001 \text{ dS/m}$, had the highest DOC concentrations in the successive extractions. Regression analysis and analysis of variances (ANOVA) were performed, and the statistical analysis ($\alpha = 0.05$) confirms that salinity in the field range ($0\text{--}4 \text{ dS/m}$) decreases the concentrations of DOC from both oxidized and reduced peat soils. In addition, the total concentration of DOC in the water extracts decreased rapidly from DDW to the solution with a K of 0.5 dS/m . The change in DOC with respect to the change in K for the oxidized soil extracts ($\Delta\text{DOC}/\Delta K$) was about 1, while the change of DOC from a K of $0.5\text{--}4 \text{ dS/m}$ was relatively small, and $\Delta\text{DOC}/\Delta K$ was about 0.14. A similar trend was also observed in the reduced soil extracts; the $\Delta\text{DOC}/\Delta K$ was 0.4 and 0.06 from DDW to an K of 0.5 dS/m and from 0.5 to 4 dS/m , respectively.

Sodicity, or SAR, also affected the quantity of the DOC leaching from both the oxidized and reduced peat soils. The pure NaCl solution (SAR of ∞) with a K of 4 dS/m extracted more DOC than the same K solution with a SAR of 0 (pure CaCl_2 solution) and than the solution with a SAR of 5. If the DDW treatment is set as the maximum removal of DOC, the pure calcium solution can reduce by 1 mg C/g soil (70%) for oxidized and 0.4 mg C/g soil (50%) for the reduced peat soils; in contrast, the pure sodium solution can reduce cumulative DOC by 0.7 mg C/g soil (50%) and 0.5 mg C/g soil (35%) for oxidized and reduced peat soils, respectively. In addition, the DOC removal ability of a solution with a SAR of 0 is insignificantly different for the successive extractions than that of a solution with a SAR of 5 (Fig. 4). The extracted DOC using solution with SAR of 5 or 0 did not show increases in the SUVA after five extractions. Such results imply that the concentration of Ca ion present at this salinity level (K of 4 dS/m) exceeds the concentration necessary to saturate available binding sites of the polyelectrolytes. Therefore, the excess Ca ions in the SAR=0 solution do not further reduce the concentration of DOC in the water extracted. In fact, the SAR values of the soil solutions from a field experiment [11] and the soil saturated paste for soil characterization in this experiment (Table 1) ranged from 2 to 8 $(\text{mmol/L})^{1/2}$. The comparatively small variation in both the DOC extracted by solutions with the small range of SAR in the field and by solutions with

a complete range of SAR in this experiment implies that the sodicity is not a major factor on the DOC leaching processes in the Delta soils.

The effects of salinity and sodicity on the nature of the DOC leaching from both the oxidized and reduced peat soils, in terms of carbon-normalized UVA, known as specific SUVA, are shown in Fig. 5. SUVA was defined as the UV absorbance at 254 nm divided by the DOC concentration, and the unit of SUVA is liters per milligram of carbon per centimeter ($\text{L mg C}^{-1} \text{ cm}^{-1}$). In general, it is proportional to the aromaticity of DOC and it has been widely used as a surrogate of THM [18,28]. Also, the SUVA of the HPOA extracted from the Delta soil-water ranged from 0.044 to 0.059, and it was higher than the SUVA of the HPIA, which ranged from 0.035 to 0.042 [11]. In our experiment, the SUVA of water extracts from both the oxidized and reduced peat soils was higher in the fifth extraction than the first extraction for all treatments. The initial extractions contained a greater amount of hydrophilic DOC compounds relative to hydrophobic aromatic compounds, reflected in the lower SUVA values. In the later extractions, the fractions of aromatic hydrophobic compounds became dominant because most of the hydrophilic DOC already had been removed by prior extractions, accounting for the increase in SUVA. In addition, the solubility of hydrophobic or aromatic compounds in the saline water was low. We can see that the highest saline solution ($K = 4 \text{ dS/m}$) had the lowest

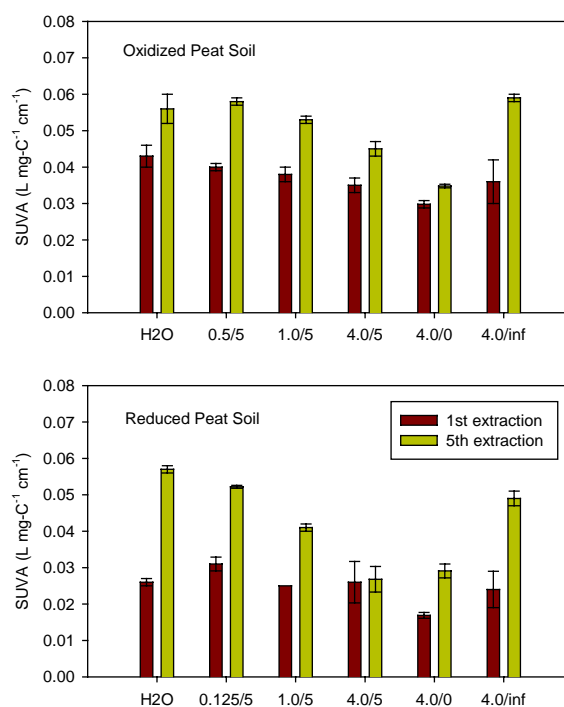


Fig. 5. Salinity and sodicity effects on the SUVA.

SUVA in the first and fifth extractions of oxidized peat soil and the fifth extraction of reduced peat soil. Regression analysis showed that SUVA decreased as salinity increases ($\alpha = 0.05$) for both soils. This result confirms that salinity in the range of 0–4 dS/m affects the aromaticity of DOC, in terms of SUVA, in these cultivated organic peat soils from the Delta.

The effects of electrolytes on the conformation of the humic substance and coagulation processes may possibly explain these phenomena. Humic substances are anionic polyelectrolytes. Their conformations are dependent on the total ionic strength or salinity of the solution. In low saline solutions, these polyelectrolytes of humic substances have stretched configurations due to mutual repulsion of the negative charges on dissociated or ionized functional groups [19]. Such conformation alterations promote soil dispersion and could result in the release of sterically trapped or weakly coordinated organic molecules into the soil solution [20], thus accounting for the high DOC extracted by low saline solutions. Selected samples from the salinity and sodicity treatments were analyzed for THMFP and the results are shown in Fig. 6. The fifth extraction of DOC from the reduced soils consistently had higher STHMFP than the first extraction of DOC for all four selected treatments. The results agreed with the prediction of SUVA.

3.3. Biotic effects—temperature and water content

Both the oxidized and the reduced peat soils were incubated 8 weeks under a range of temperatures and water contents. The results of DOC, SUVA, and STHMFP are summarized in Fig. 7. First of all, we noted that the concentrations of extracted DOC in the oxidized peat soils were decreased in the non-flooded conditions. About 50% of the DOC in the oxidized peat soils, which had a water content of 0.3 in one sample,

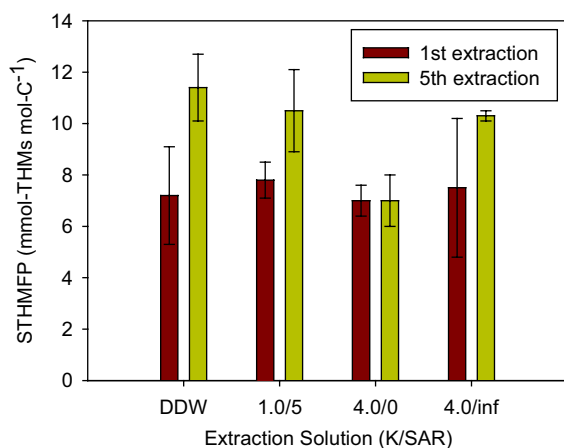


Fig. 6. STHMFP of extracted DOC from reduced peat soils.

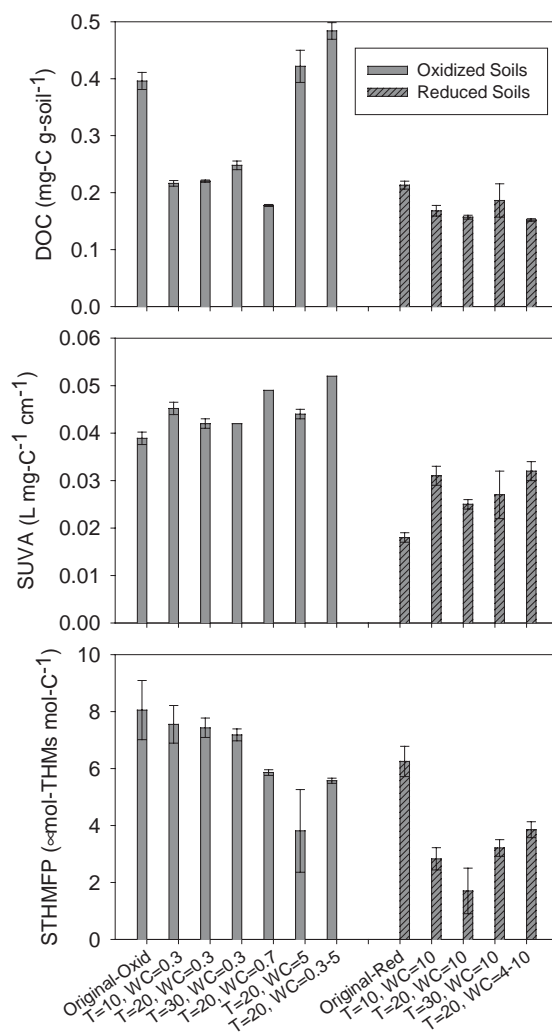


Fig. 7. The results of DOC, SUVA and STHMFP of incubation experiments.

and 0.7 in another, was lost in the 8-week incubations. The soils with water content at 0.7 had the lowest DOC among treatments. Also, the concentrations of DOC remaining in the soils increased slightly with temperature, and the soils at 30°C had the highest extracted DOC. In contrast to the non-flooded conditions, the DOC increased in the soils under flooded conditions or in flooded and non-flooded cycles. The flooded conditions slightly increased DOC to 0.42 mg C/g soil from 0.40, an increase of about 5%. The soils with flooded and non-flooded cycles had the highest concentrations of DOC, and the increase was about 20% after 8-week incubations. For the reduced peat soils, the concentrations of DOC also decreased after incubation in all the treatments but the losses were only about 10%. The soils incubated at 30°C also had the highest extracted DOC,

but the concentrations of DOC did not follow the temperature trends. The DOC from the soils with flooded and non-flooded cycles did not increase either.

The SUVA values of extracted DOC from all the treatments were increased in the 8-week incubation. The extracted DOC from the soils under flooded and non-flooded cycles had the highest increases in SUVA in both the oxidized peat soils and the reduced peat soils. It increased from 0.039 to 0.052 for the oxidized peat soils, and from 0.018 to 0.032 for the reduced peat soils. Also, the SUVA of extracted DOC slightly decreased with increasing temperature in the non-flooding condition. In other words, the oxidized peat soils with lower extracted DOC had a higher SUVA value under non-flooded conditions. The soils with 0.7 water content had the lowest DOC, but had the highest SUVA value in the non-flooded treatments. In contrast to the increases of SUVA, the STHMFP in all the treatments was decreased after incubation. In the non-flooded conditions, STHMFP of extracted DOC from the oxidized peat soils with water content at 0.3 was reduced by about 10% or 1 mmol THMs molC⁻¹. In the flooded conditions, STHMFP of both oxidized and reduced peat soils was reduced by more than 50%. Oxidized peat soils under non-flooded conditions were further analyzed by XAD fractionation, and the results are shown in Fig. 8. There were slight increases in HPOA and NA-HPIA and decreases in HPIA and HPON after 8-week incubation. However, all the changes, less than 10%, were statistically insignificant.

The results of our incubation experiment show that the quantity and the nature of DOC are affected by environmental factors. Environmental factors can affect the soil microbial population and their activity and eventually affect the rate of degradation on the SOM and the concentrations of DOC in soils. Among the different factors, our results indicate that the major condition for DOC and THM precursor production in

the Delta are the oxidized peat soils under flooded condition and under flooded and non-flooded cycles. Flooded conditions create anaerobic conditions. Microbial decomposition of SOM differs under different redox conditions. While oxidizing the reduced organic matter, microbes use electron acceptors, such as oxygen, nitrate, Mn, Fe(III), sulfate or CO₂ to complete the reactions. The availability of these electron acceptors greatly affects the amount of energy produced and the end products, and thus, the degree of organic matter decomposition. Under aerobic conditions, microorganisms decompose SOM at a much faster rate with CO₂ and H₂O as end products [21]. In contrast, decomposition rates of SOM under anaerobic conditions are much slower with production of reduced compounds such as H₂S and CH₄. The degree of organic matter decomposition at different redox conditions theoretically vary, releasing different amounts of dissolved organic matter with different compositions into the soil solution, thus affecting water quality in terms of THM formation potentials. Sihombing et al. [9] showed that the local oxidizing/reducing environment greatly alters the gross structural group content of the SOM. In addition, the flooded and non-flooded cycles or aerobic-anaerobic cycles in the fields could promote a diversity of microorganisms and provide different pathways to decompose the refractory peat materials throughout the soil profile. Thus, soil water content and flooded and non-flooded cycles may affect both the mechanism and the rate of decomposition of peat soil, and may also affect the quantity as well as the nature of DOC leaching from the cultivated peat land.

In addition to the soil water content, temperature is one of the main factors determining microbial activity in the soil environment. As temperature increases, the rate of microbial oxidation of organic matter in peats increases [22]. This effect has been observed in numerous studies on peat land subsidence and CO₂ fluxes (e.g., [23]). Carbon dioxide emissions are significantly correlated with soil temperature in the Delta [24]. It has been demonstrated that DOC concentrations in stream waters [25] and soil solutions [26] are highest during the summer and autumn months and correspond to elevated seasonal temperatures. Our data show that extracted DOC from the oxidized peat soil slightly increased with increasing temperature. However, the DOC-temperature relationship was not observed in the reduced peat soils. The effect of temperature on DOC production is not certain.

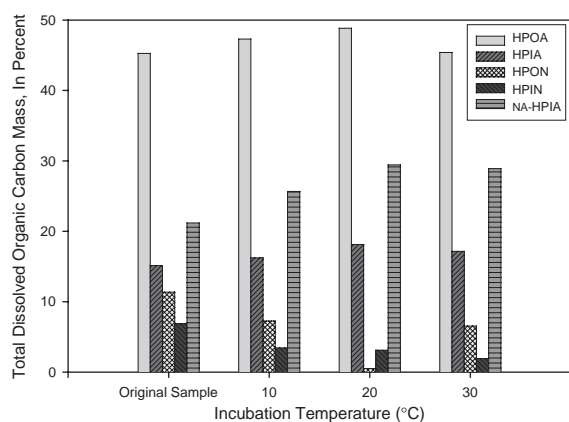


Fig. 8. Temperature effects on the fractionation of extracted DOC from oxidized peat soil after 8-week incubation.

4. Conclusion

Current agricultural practices in the Sacramento-San Joaquin Delta create seasonal and short-term flooded and non-flooded cycles in the fields. These practices can

affect the soil salinity, sodicity and respiration and eventually alter the DOC concentrations present in agriculture drainage. The results of our abiotic study show that DOC, as soil salinity increases or sodicity decreases, can flocculate with metal cations and be stored in the fields. The salt accumulation, which coagulates DOC in soils, is not the factor explaining high DOC in the drainage of summer irrigation periods. On the other hand, this coagulated DOC is the source of high DOC in winter salt leaching regimes. Also, two environmental factors (temperature and water content) affecting DOC production were examined. Temperature is not the major factor in DOC production in the Delta. Flooding conditions and flooded and non-flooded cycles do not increase the DOC in reduced peat soil. Only the flooded conditions and flooded and non-flooded cycles in oxidized peat soil yield a significant increase of DOC after an 8-week incubation. Thus, we believe the wetting processes increased the DOC in oxidized peat soil in the Delta and salinity affects its solubility and mobility.

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