Seasonal Losses of Dissolved Organic Carbon and Total Dissolved Solids from Rice Production Systems in Northern California

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Water quality concerns have arisen related to rice (*Oryza sativa* L.) field drain water, which has the potential to contribute large amounts of dissolved organic carbon (DOC) and total dissolved solids (TDS) to the Sacramento River. Field-scale losses of DOC or TDS have yet to be quantified. The objectives of this study were to evaluate the seasonal concentrations of DOC and TDS in rice field drain water and irrigation canals, quantify seasonal fluxes and flow-weighted (FW) concentrations of DOC and TDS, and determine the main drivers of DOC and TDS fluxes. Two rice fields with different straw management practices (incorporation vs. burning) were monitored at each of four locations in the Sacramento Valley. Fluxes of DOC ranged from 3.7 to 34.6 kg ha^{-1} during the growing season (GS) and from 0 to 202 kg ha^{-1} during the winter season (WS). Straw management had a significant interaction effect with season, as the greatest DOC concentrations were observed during winter flooding of straw incorporated fields. Fluxes and concentrations of TDS were not significantly affected by either straw management or season. Total seasonal water flux accounted for 90 and 88% of the variability in DOC flux during the GS and WS, respectively. Peak DOC concentrations occurred at the onset of drainflow; therefore, changes in irrigation management may reduce peak DOC concentrations and thereby DOC losses. However, the timing of peak DOC concentrations from rice fields suggest that rice field drainage water is not the cause of peak DOC concentrations in the Sacramento River.

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Rice fields dominate the landscape of California's Sacramento Valley, with approximately 200,000 ha of land under production (California Department of Food and Agriculture, 2009). Historically, rice straw was burned after harvest to inexpensively remove straw biomass for ease of tillage and to mitigate pest and disease problems. The burning of rice straw emits smoke and other airborne pollutants which affect overall air quality and has been linked to asthma hospitalizations (Jacobs et al., 1997). State regulations have commanded a drawdown in the burning of rice straw (California Rice Straw Burning Reduction Act AB1378, 1991), and currently, the burning of rice straw is only permitted under specific conditions. In 2002, <7% of the rice acreage was burned and <13% was burned in 2003 (Hill et al., 2006). The most popular method of straw disposal includes incorporating straw into the soil after harvest followed by flooding during winter months to enhance decomposition. This change in straw management has lead to the creation of habitat for migratory water fowl (Brouder and Hill, 1995) which leads to further straw decomposition (Bird et al., 2000). Straw incorporation and winter flooding have also been shown to have the agronomic benefit of requiring less fertilizer nitrogen to achieve optimum yields (Linquist et al., 2006). In addition, incorporation of straw has lead to an increase in carbon (C) sequestration rates in California's rice fields (Kroodsma and Field, 2006). However, these benefits come at an economic cost through increased water use, additional tillage practices, and pesticide applications.

Water quality concerns have arisen in relation to the potential increase in DOC concentration and export caused by combination of straw incorporation and winter flooding. The DOC can react with chlorine during drinking water disinfection and lead to the formation of harmful byproducts, such as trihalomethanes (Xie, 2004). The maximum contaminant level for trihalomethane is 80 μg L^{-1} (USEPA, 2009) and efforts are currently underway to assess and define safe levels of DOC for drinking water intakes. The large

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Abbreviations: B, burned; C, carbon; DOC, dissolved organic carbon; FW, flow-weighted; GS, growing season; I, incorporated; MF, maintenance flow; TDS, total dissolved solids; WS, winter season.

input of organic C (as straw biomass) to rice fields after harvest can impact the terrestrial C cycle by increasing soil water DOC concentrations (Katoh et al., 2005), and by increasing the export of DOC to surface waters. The surface hydrology of the Sacramento Valley is dominated by engineered waterways, including peripheral drainage canals that transport used irrigation water from agricultural fields to large flowing surface waterways, which eventually flow into the Sacramento River. The Sacramento River is the major drinking water source for the Sacramento metropolitan area and contributes 84% of the freshwater supply to the Sacramento-San Joaquin Delta, which itself is a drinking water source for an additional 22 million California residents. Specific organic compounds, such as pesticides used in rice production, have been detected in the Sacramento River (Finlayson et al., 1993; Crepeau and Kuivila, 2000; Orlando and Kuivila, 2004) indicating that rice production can affect the downstream water quality. Therefore, DOC exported from rice fields may represent a large allochthonous input into Sacramento Valley surface waters, and perhaps the Delta as well. Median concentrations of DOC in the Sacramento River (measured between 1980 and 2000) have been shown to be <2 mg L^{-1} (Saleh et al., 2003). Chow et al. (2007) reported average DOC concentrations in the lower Sacramento River between 1.48 and 1.92 mg L^{-1}. Surface waterways within the Sacramento Valley that receive rice field drainage water, such as the Colusa Basin Drain, have higher average DOC concentrations compared to the Sacramento River and are often the highest in the Sacramento Valley (Chow et al., 2007; Saleh et al., 2003).

Dissolved organic C has environmental and ecological implications beyond trihalomethane formation, such as facilitated transport of metals and organic pollutants (Chiou et al., 1986; Römkens and Dolfing, 1998; Tetzlaff et al., 2007; Schuster et al., 2008) and as an energy source for aquatic microorganisms (Amon and Benner, 1996). Winter flooding of rice fields has likely caused changes to the aquatic C cycle in the Sacramento Valley, as organic forms of C are transferred from the rice cultivated landscape. Other drinking water characteristics such as color, taste, and odor can be affected by DOC, and also can be affected by the concentration of total dissolved solids (TDS) (Bruvold, 1970). The secondary drinking water standard for TDS, which are comprised of dissolved salts, carbonates, metals, and organics, is set at 500 mg L^{-1} (AWWA Staff, 2003; USEPA, 2009).

Field-scale quantification of DOC and TDS fluxes from rice production systems have not been measured and the effect of straw management practices on DOC and TDS concentrations and fluxes have not been evaluated. In addition, seasonal dynamics of DOC and TDS concentrations from rice field outlets remain largely unknown. The objectives of this study were to: (i) evaluate seasonal concentrations of DOC and TDS in rice field drain water, supply canals, and drainage canals in the Sacramento Valley; (ii) quantify seasonal fluxes and flow-weighted (FW) concentrations of DOC and TDS from burned and straw-incorporated rice fields, and (iii) determine the main drivers of DOC and TDS flux and concentration in rice field drainage water.

Materials and Methods

This study was conducted on rice grower fields in California's Sacramento Valley between 1 Apr. 2006 and 30 Mar. 2008 (Fig. 1). The cooperating grower sites were located near Marysville, Biggs, Arbuckle, and Willows. Each site was located in a different rice growing area of the valley and represents a range of soil types and characteristics (Table 1). At each site, two fields of varying straw management were identified for this study: straw incorporation (I) or burning (B). Each individual field varied with respect to overall water management during the growing season (GS, 1 April–30 September) and the winter season (WS, 1 October–30 March). During the growing season, all rice fields were flooded at the time of planting. Aerial seeding occurred 3 to 5 d after the onset of flooding. Early in the growing season when pesticides were applied, some fields were completely drained and others remained flooded but did not have outflow. After pesticide application, the drained fields were immediately reflooded. Once the hold time for each pesticide expired, most fields were managed with maintenance flow (MF), where a continuous outflow of water was maintained to establish a consistent depth of water in the field. Some growers did not have any water leaving their fields and instead managed flood water depth through regulation of input water. Fields were completely drained at least 3 wk before harvest. In the winter season, straw incorporated fields were flooded during the time period of late October to late February to aid in rice straw decomposition. All straw incorporated fields were winter flooded with the exception of Arbuckle-I in 2006. During winter flooding on straw incorporated fields, water was managed with MF or through regulation of input water (Table 2). The owner of Marysville-B decided to flood the field during the WS of 2006 to create a habitat for waterfowl and was managed with MF. Water management on all other burned fields included either flooding with rainwater (outlet blockage) or allowing rainwater to immediately run off of the fields (no outlet blockage). After the growing season in 2006, two fields were taken out of rice production (Marysville-B and Arbuckle-I). A new straw-incorporated field site was identified at Arbuckle (Table 2). At the Marysville site, the Marysville-I for the GS of 2006 was burned (becoming Marysville-B) and a new straw incorporated site was identified (Table 2). Before the WS of 2007, Marysville-B and Willows-B were unable to be burned because of unfavorable weather conditions. No new burned fields were able to be identified at Marysville and Willows for the 2007 winter season. The field which was Marysville-B for the 2007 growing season was identified as the straw-incorporated field for the 2007 winter season (Table 2).

Each field had one or two water inlets that allowed irrigation from supply canals and one water outlet that drained water into peripheral drainage canals. Outflow was measured by installing a rectangular weir fitted with a Global-Water pressure sensor/data logger (Gold River, CA) in the main outlet of each field. The pressure sensor recorded the water height over the weir every 15 min. A ruler was placed on each weir to calibrate the pressure sensors and to estimate flow rates when pressure sensors were unable to be installed or malfunctioned. For the 2006 growing season, outflow was measured entirely

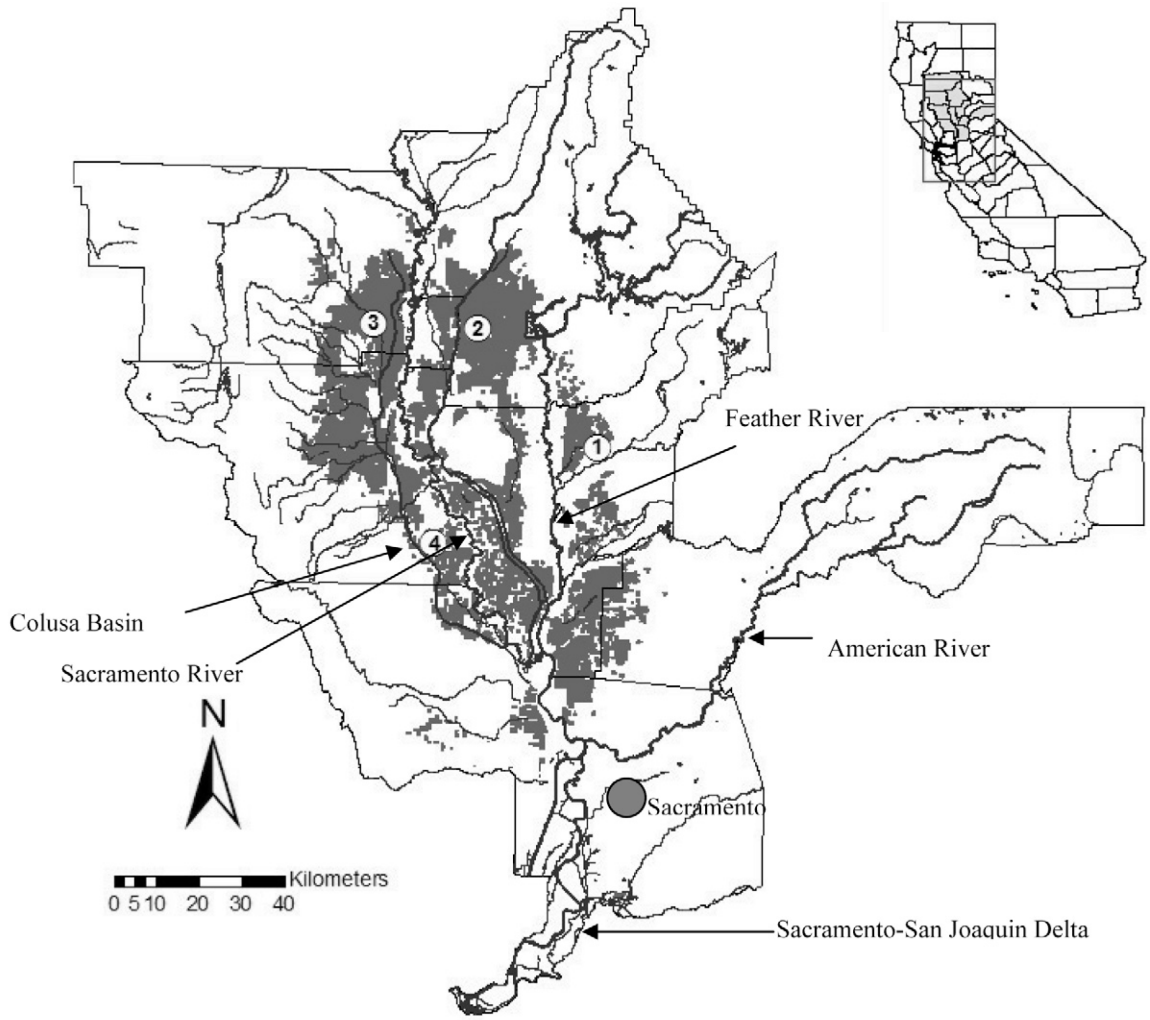

Fig. 1. Locations of experimental sites (1 = Marysville, 2 = Biggs, 3 = Willows, 4 = Arbuckle) and major surface water bodies in Sacramento Valley, CA. Gray areas represent the rice growing acreage of the Sacramento Valley.

Table 1. Field sizes, soil classification, and soil characteristics, including pH, cation exchange capacity (CEC), total carbon (TC), soil organic carbon (SOC), and texture of 10 rice fields in the Sacramento Valley.

Field	Location	Size	Soil classification†	pH	CEC	TC	SOC	Sand	Silt	Clay
		ha			meq 100 kg^{-1}	g kg^{-1}		%		
1	Marysville	25.9	Fine, mixed, active, thermic Abruptic Durixealfs	4.8	14.2	10.4	9.3	37.5	35.0	27.5
2	Marysville	24.3	Fine, mixed, active, thermic Abruptic Durixealfs	4.8	16.5	11.1	9.3	35.5	29.3	35.3
3	Marysville	9.3	Fine-loamy, mixed, active, thermic Aquic Haploxerepts Fine, mixed, active, thermic Abruptic Durixeralfs	4.8	14.1	17.6	11.2	41.0	39.0	20.0
4	Biggs	42.1	Very-fine, smectitic, thermic Xeric Epiaquerts Very-fine, smectitic, thermic Xeric Duraquerts	5.0	52.7	17.1	11.1	12.0	24.8	63.3
5	Biggs	57.9	Very-fine, smectitic, thermic Xeric Epiaquerts Very-fine, smectitic, thermic Xeric Duraquerts	5.2	52.0	19.1	12.1	15.8	24.0	60.3
6	Arbuckle	52.2	Fine, smectitic, thermic Xeric Endoaquerts	6.0	53.0	20.9	15.4	8.4	35.4	56.3
7	Arbuckle	58.7	Fine, smectitic, thermic Xeric Endoaquerts	6.2	49.5	19.2	13.1	7.0	39.0	54.0
8	Arbuckle	68.0	Fine, smectitic, thermic Xeric Endoaquerts	6.0	52.6	19.7	13.9	8.8	37.8	53.5
9	Willows	45.3	Fine, smectitic, thermic Sodic Endoaquerts	5.8	38.1	21.1	17.0	16.8	42.3	41.0
10	Willows	32.4	Fine, smectitic, thermic Sodic Endoaquerts Fine, smectitic, thermic Typic Haploxererts	5.8	32.3	20.3	18.1	22.4	40.5	37.1

† Representing >75% of the soil area.

from observed weir heights. Weirs were used to measure water flow during periods of maintenance flow, but were removed from field outlets to allow the field to be drained early in the growing season and at the end of each flooding season. To estimate water loss during the drain periods, four to eight rulers were placed in each field (one ruler per 2 to 11 ha) and depth of water was recorded before, during, and after the drain. Early growing season and end of winter season drain volumes were

Table 2. Agronomic and water management practices of 10 rice fields in the Sacramento Valley. Early water management practices during the growing season include: no early flooding (N), flooding with water held (H), or flooding followed by a complete field drain (D). Mid-growing season water management practices include: no water drained (N), maintenance flow (MF), or accidental water loss as leakage (Leak). Winter water management practices include: flooding with water held (H), flooding with maintenance flow (MF), flooding with rainfall (RF), or no flooding (NF). For the NF management, outflow occurred as surface runoff.

Field	Site	Trt†	Planting date	Variety	Flooding date	Water management Early	Water management Mid	Drain date	Yield	Trt†	Burn date	Incorp date	Flood date	Water management	Drain date‡
									Mg ha^{-1}						
				2006 Growing Season								2006 Winter Season			
1	Marysville	I	26 May	Koshihikari	22 May	N	MF	6 Sept.	6.5	B	19 Nov.		14 Nov.	MF	14 Feb.
2	Marysville	B	11 May	Koshihikari	7 May	N	MF	31 Aug.	7.6				–	–	–
3	Marysville									I		16 Nov.	11 Nov.	MF	14 Feb.
4	Biggs	I	15 May	M202	12 May	H	MF	3 Sept.	13.3	I		17 Oct.	21 Oct.	MF	29 Jan.
5	Biggs	B	8 May	M206	8 May	H	MF	21 Aug.	11.0	B	16 Oct.			NF	none
6	Arbuckle	I	12 May	M206	12 May	D	MF	22 Aug.	11.6						
7	Arbuckle									I		none	none	RF	none
8	Arbuckle	B	11 May	M206	11 May	D	MF	22 Aug.	12.9	B	21 Oct.			RF	none
9	Willows	I	14 May	M204	14 May	N	Leak	7 Sept.	na	I		1 Nov.	8 Nov.	H	1 Feb.
10	Willows	B	25 May	M205	25 May	N	Leak	14 Sept.	11.0	B	28 Oct.			RF	none
				2007 Growing Season								2007 Winter Season			
1	Marysville	B	22 May	Koshikihari	17 May	N	MF	12 Sept.	5.8	I		19 Oct.	20 Oct.	MF	20 Feb.
2	Marysville														
3	Marysville	I	26 May	Koshikihari	21 May	N	MF	12 Sept.	7.2						
4	Biggs	I	24 Apr.	M206	20 Apr.	H	MF	10 Aug.	12.4	I		28 Sept.	8 Oct.	MF	28 Jan.
5	Biggs	B	16 Apr.	M205	13 Apr.	D	MF	13 Aug.	13.5	B	1 Oct.			NF	
6	Arbuckle														
7	Arbuckle	I	27 Apr.	M202	27 Apr.	D	MF	21 Aug.	11.9	I		20 Oct.	26 Nov.	MF	5 Feb.
8	Arbuckle	B	28 Apr.	M206	27 Apr.	D	N	21 Aug.	12.6	B	8 Oct.			RF	8 Feb.
9	Willows	I	30 Apr.	M205	24 Apr.	N	N	27 Aug.	11.7	I		1 Oct.	12 Oct.	H	15 Feb.
10	Willows	B	30 Apr.	M205	24 Apr.	N	N	27 Aug.	11.2						

† Trt, straw management treatment; I, incorporated; B, burned.

‡ The drain date was the date when the outlets were unblocked, allowing field to be completely drained; none indicates that fields did not have standing water at release date.

calculated as the product of the water depth before and after drainage and the rice field area. The end of growing season final drain volumes were calculated in the same manner, correcting for volume displacement of rice plants. Rainfall data was collected by the University of California Integrated Pest Management Program (2009) and the official rainfall monitoring stations were within 15 km of each corresponding field site.

Samples were collected from supply canals across from the field inlets, from rice field outlets as water flowed over the weir, and from peripheral drains 10 to 30 m downstream of the field outlet. Samples were collected on a weekly or biweekly basis, with more intensive sampling conducted following the onset of MF, during the final drain, or after rainfall events. Water samples were stored on ice and filtered with a 1.5 μm glass fiber filter within 24 h of sample collection. Samples were frozen until subsequent analyses could be performed. Although DOC is often operationally defined as organic C passing through a 0.45 μm filter, data reported by Chow et al. (2005) indicate little difference in DOC concentrations between 0.45 and 1.25 μm pore sizes. Our selection of a slightly larger pore size reflects our desire to account for as much of the nonsediment bound organic C as possible. Filtered samples were analyzed for DOC using a Shimadzu TOC-V CSN Analyzer (Kyoto, Japan). Total dissolved solids were determined using an Oakton CON11 handheld conductivity/TDS meter (Vernon Hills, IL), which was calibrated at 25°C. During the growing season, three subseasons were identified: (1) early season, (2) mid-season, and (3) the final drain. Early-GS drainage occurred as drainflow before pesticide application, field draining for pesticide application, or the first 30 d of drainflow. Mid-GS drainage included the remaining drainflow up to the final drain. Three subseasons were also identified within the winter season: (1) early winter season, (2) mid-winter season, and (3) the final drain. The early-WS included the first 30 d of MF and the mid-WS included the remaining period of MF. Flooding season and subseason fluxes (kg ha^{-1}) of DOC and TDS were calculated as the sum of the products of each sample concentration (mg L^{-1}) and the flow-proportional volume associated with that sample. The flow-proportional volume was calculated as the total outflow occurring between days that are midway between each sampling date. Flow-weighted DOC and TDS concentrations were calculated for each season and subseason by dividing the total solute flux by the total water flux of each period.

Yield and biomass measurements were collected before harvest by collecting aboveground plant samples from an area of 0.59 m^2 at four locations within each field. Plant samples were oven-dried at 60°C, rice grain was separated from the plant, and both rice grain and straw biomass were weighed. Rice yields were reported on a 14% moisture basis and straw biomass was reported on a dry weight basis. To estimate the amount of residue that remained after burning, remaining plant biomass was collected from an area of 0.59 m^2 at four locations within the field. Soil samples (0–15 cm depth, 6 cm in diameter) were collected from each harvested area in 2006, except for field sites added after the 2006 growing season (i.e., Marysville-I and Arbuckle-I) where soil samples were collected in 2007. Soil samples were air dried, ground, and analyzed for pH (saturated paste method; U.S. Salinity Laboratory Staff, 1954), CEC (barium acetate saturation and calcium replacement method; Rible and Quick, 1960), total carbon (combustion gas analyzer method, AOAC, 1997), soil organic C (modified Walkley–Black method; Nelson and Sommers, 1996), and texture (hydrometer method; Sheldrick and Wang, 1993) by the University of California Agriculture and Natural Resources Laboratory.

Statistics were performed using SAS (SAS Institute, Inc., 1999). Analysis of variance (Proc. GLM) was conducted on the randomized complete block, blocked split plot design, with site as the block effect, straw management as the whole plot treatment, year as the split plot block effect, and flooding season as the split plot treatment. When the year effect was not significant in the model, this effect was removed and the model was run as a randomized complete block, split plot design. To evaluate the effect of subseason, ANOVA was conducted in the same manner, with subseason, instead of season, as the split plot treatment. Regression analysis was preformed on log-transformed variables between water flux and DOC and TDS flux (Proc. REG). The resulting linear model was transformed to the equation:

$$L = \mathrm{a}\, Q^{\mathrm{b}}$$

where L is the solute flux and Q is the water flux (nonlog transformed variables). Slope values (b) < 1 indicate that larger outflows are associated with lower seasonal FW-concentrations and values > 1 indicate larger outflows are associated with greater seasonal FW-concentrations compared to low outflows.

Results

Total water outflow across all fields ranged from 300 to 4720 m^3 ha^{-1} during the growing season (Table 3). Total water outflow across all incorporated fields that were flooded during the winter season ranged from 680 to 8360 m^3 ha^{-1} (Table 3). Only one burned field was flooded; in the WS of 2006 Marysville-B was flooded and the total water outflow was 13,060 m^3 ha^{-1} (Table 3). In burned, unflooded fields, rainfall caused between 0 and 1100 m^3 ha^{-1} of outflow (Table 3). Across all field sites, winter rainfall ranged from 166 to 249 mm in 2006 and 375 to 496 mm in 2007. The outflow from Biggs-B represented 2.6 and 6.4% of the winter rainfall in 2006 and 2007, respectively. In 2007, Arbuckle-B used rainfall to flood the field, and the outflow represented 22.2% of the seasonal rainfall. Rice yields ranged between 5.8 and 7.6 Mg ha^{-1} for the Koshihikari varieties, and 11.0 and 13.5 Mg ha^{-1} for all medium grain varieties (Table 2). Based on straw biomass collected at harvest, incorporation of straw added between 3.7 to 5.3 Mg ha^{-1} of organic C to the soil in 2006 and between 2.7 and 4.4 Mg ha^{-1} of organic C to the soil in 2007. The burning of straw varied from site to site. Burning removed between 80 and 90% of the straw biomass across all sites and years. Overall, burning of these sites removed similar amounts of biomass as was reported by Linquist et al. (2006) (73–80%).

Dissolved Organic Carbon and Total Dissolved Solids Concentrations

Among all collected water samples, DOC concentrations ranged between 0.6 and 77.7 mg L^{-1} for rice field outlets, 0.5 and 79.9 mg L^{-1} in peripheral drainage canals, and below detection limit (< 0.05 mg L^{-1}) and 13.6 mg L^{-1} in supply canals (Fig. 2). Median DOC concentrations in outlets, drainage canals, and supply canals were 9.5, 8.0, and 1.7 mg L^{-1}, respectively. Although the DOC concentrations from outlets exhibited large variability in each month, clear trends in monthly concentrations were detected (Fig. 2). The largest DOC concentrations were observed in October and November, the first 2 mo of the winter flooding season. The monthly patterns of DOC concentrations were similar between rice field outlets and peripheral drain canals. In supply canals, the DOC concentrations were generally lower than in the outlets and drain canals. Furthermore, the variation in DOC concentration in the supply canals was typically low, with the greatest variation occurring in the summer months.

Among all collected water samples, TDS concentrations ranged between 6.8 to 794 mg L^{-1} in rice field outlets, with a median concentration of 138 mg L^{-1}. The TDS concentrations ranged from 37 to 900 mg L^{-1} and 24.1 to 637 mg L^{-1} in peripheral drain canals and supply canals, with median concentrations of 89.2 and 51.8 mg L^{-1}, respectively. Among all collected samples, only 1.3% of all outlet samples exceeded the EPA drinking water standards (500 mg L^{-1}), while 7.1% of peripheral drain samples exceeded these standards. No trend was detected for TDS concentrations in rice field outlets, peripheral drains, or supply canals (Fig. 2). However, monthly patterns of TDS concentrations were noticeably dissimilar to monthly DOC concentrations. Based on median DOC and TDS concentrations, DOC typically represents only 7% of the TDS.

Seasonal Fluxes and Flow-Weighed Concentrations

Seasonal DOC fluxes ranged from 3.7 to 34.6 kg ha^{-1} during the growing season and from 0 to 202 kg ha^{-1} during the winter season. Although the winter season had over twice the average DOC flux compared to the spring season (35.4 vs. 14.2 kg ha^{-1}, respectively), the DOC fluxes were not significantly different between these flooding periods (P = 0.14). Seasonal fluxes of TDS were also not significantly different between the growing and winter season (293 and 232 kg ha^{-1}, respectively; P = 0.38). Across all flooding seasons, no differences in DOC or TDS flux between burned and straw-incorporated fields were determined. Furthermore, no interaction effect between straw management and season on DOC or TDS flux was observed.

Table 3. Seasonal water, dissolved organic carbon (DOC), and total dissolved solid (TDS) fluxes of 10 rice fields in the Sacramento Valley (na = data not available).

		Growing season 2006			Winter season 2006				Growing season 2007			Winter season 2007			
Field	Location	Water flux	DOC flux	TDS flux	Water flux	Rainfall	DOC flux	TDS flux	Water flux	DOC flux	TDS flux	Water flux	Rainfall	DOC flux	TDS flux
		$m^3\ ha^{-1}$	—kg ha^{-1}—		$m^3\ ha^{-1}$	mm	—kg ha^{-1}—		$m^3\ ha^{-1}$	—kg ha^{-1}—		$m^3\ ha^{-1}$	mm	—kg ha^{-1}—	
1	Marysville	2020	9.1	114	13,060	245	94.5	949	430	3.7	31	2270	430	31.3	166
2	Marysville	4640	22.1	258											
3	Marysville				900	245	19.7	88	800	6.8	59				
4	Biggs	4720	18.6	258	6160	249	202	645	3350	21.7	341	8360	375	82.8	567
5	Biggs	3140	18.7	193	60	249	0.5	5.2	4540	34.6	320	240	375	1.7	26
6	Arbuckle	2290	12.7	110											
7	Arbuckle				0	166	0	0	2550	24.2	641	1570	496	16.9	268
8	Arbuckle	3270	20.8	408	0	166	0	0	750	6.3	158	1100	496	11.3	159
9	Willows	1290	13.7	282	680	174	22.0	139	1240	8.0	319	1300	393	12.8	237
10	Willows	300	2.0	59	0	174	0	0	640	3.6	141				

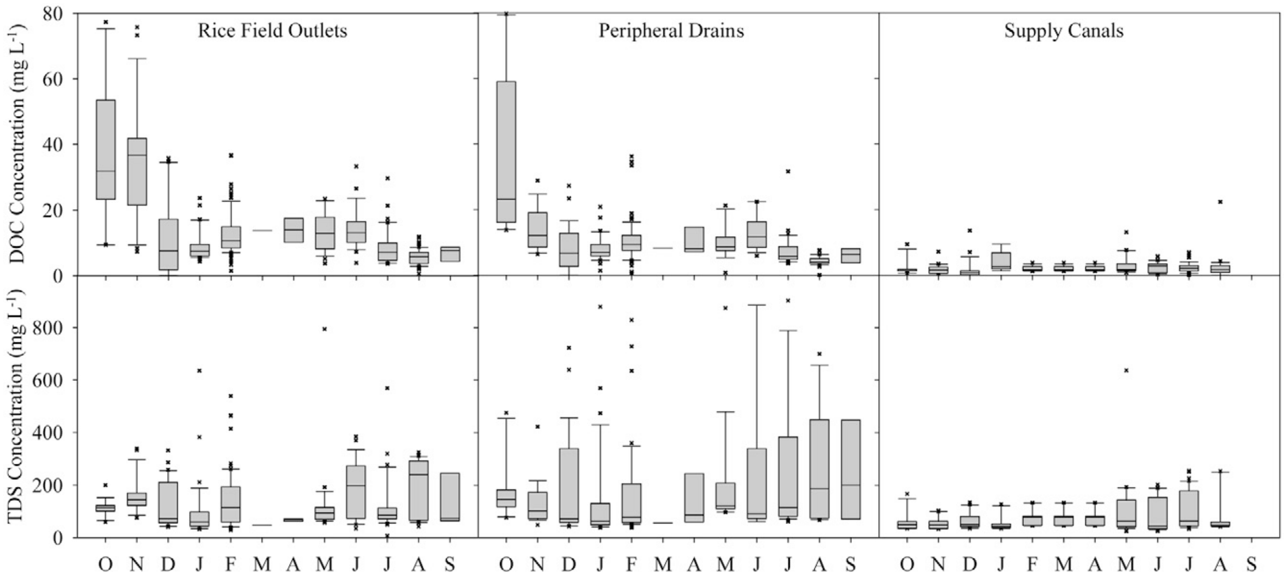

Fig. 2. Box-plot of monthly dissolved organic carbon (DOC) and total dissolved solid (TDS) concentrations from samples collected from rice field outlets, peripheral drainage canals, and irrigation supply canals of 10 different rice fields in the Sacramento Valley.

Straw management had a significant effect on seasonal FW-DOC concentration (P = 0.03), as straw incorporated fields had a higher average seasonal FW-concentration (12.5 mg L^{-1}) compared to burned fields (7.2 mg L^{-1}). The average FW-DOC concentration for the winter season (14.9 mg L^{-1}) was double of that for the growing season (6.8 mg L^{-1}) but this difference was not statistically significant (P = 0.5). There was a significant interaction effect between season and straw management (P = 0.01), which was evident during the WS, as straw-incorporated fields had a greater average FW-DOC concentration compared to burned fields (18.8 vs. 8.1 mg L^{-1}). However, the two winter seasons had different FW-DOC concentrations as incorporated fields in the WS of 2006 had nearly a three times greater average FW-DOC concentration than incorporated fields in the WS of 2007 (29.0 vs. 11.1 mg L^{-1}).

Straw management had a significant effect on sub-season FW-DOC concentrations (P = 0.02), while the effect of sub-season was not significant (P = 0.13). There was a significant interaction effect (P = 0.03) between straw management and subseason suggesting that while incorporated fields had greater FW-DOC concentrations than burned fields, the patterns of FW-DOC concentrations were also different. This was evidenced by the large FW-DOC concentration in early WS for the incorporated fields (Fig. 3). Within the winter season, the average FW-DOC concentration for the first month of outflow in incorporated fields was 35.8 mg L^{-1}, while the remaining period of outflow was 16.0 mg L^{-1} and the final drain was 15.5 mg L^{-1} (Fig. 3). These concentrations were two to four times higher than sub-seasonal FW-DOC concentrations from burned fields. The FW-DOC concentration from Marysville-B in early-WS of 2006 (the lone burned field with early-WS outflow) was 7.7 mg L^{-1}; across all burned fields with outflow, the average FW-DOC concentrations for the mid-WS and final drain of the WS were 7.0 and 9.5 mg L^{-1}, respectively. Each straw incorporated field that had MF exhibited the same trend of decreasing DOC concentrations over the WS [Biggs-I in 2006, Marysville-I in 2007, and Biggs-I in 2007 (Fig. 4); Marysville-I in 2006 and Arbuckle-I in 2007 (data not shown)]. Only a slight decreasing trend was observed for Marysville-B in 2006 (Fig. 4). Similar decreasing patterns in DOC concentration were also observed during the growing season (data not shown). At Willows, the in-field DOC concentrations appeared to decrease over time without any DOC being exported from the field with drain water (Fig. 5).

In contrast to DOC, seasonal FW-TDS concentrations were not significantly different between straw management treatments. Additionally, FW-TDS concentrations were not significantly different among seasons and no interaction effect between straw management and season was observed. Average seasonal FW-TDS concentrations were 120 mg L^{-1} for winter and 130 mg L^{-1} for the growing season. In addition, FW-TDS concentrations were not significantly different across subseasons and there was not a significant interaction effect between straw management and subseason (Fig. 6).

The relationship between log-transformed values of water flux and DOC flux was significant, with seasonal outflow accounting for 90 and 88% of the variability in DOC flux during the GS and WS, respectively. Across all fields, the slope for the GS outflow-DOC flux relationship was 0.87. The 90% confidence limit for this slope was between 0.74 and 1.00, indicating that based on a slightly larger confidence limit, this slope would be significantly <1, providing evidence that an increase in outflow through greater water usage dilutes the seasonal FW-DOC concentration. The slope of the outflow-DOC flux relationship during the WS was not significantly different than 1, indicating that greater total outflow, originating from flooding and rainfall, did not dilute the FW-DOC concentration. Water flux accounted for 49 and 90% of the TDS flux during the GS and WS, respectively. Neither seasonal slope of the outflow-TDS flux relationship was significantly different than 1.

Discussion

Dissolved Organic Carbon in the Sacramento Valley

The highest DOC concentrations in rice field outflow occurred at the onset of winter flooding of straw incorporated fields (Fig. 2) in October and November. The pattern of high DOC concentrations at the onset of drainflow, followed by a sharp decrease over time (Fig. 2 and 3), was observed in each winter flooded rice field where maintenance flow occurred. Stepanauskas et al. (2005) reported that in 2000 and 2001 peak DOC concentrations in the Sacramento River occurred between January and March. Since seasonal patterns of DOC concentrations differ between rice fields and the mouth of the Sacramento River (Fig. 2 vs. Stepanauskas et al., 2005), rice field DOC was not likely the main contributor to the Sacramento River during these peak periods. Consequently, this would indicate that the contribution of DOC from rice production systems in the Sacramento Valley toward the Delta would be minimal. However, it is probable that rice production systems are a main source of DOC for upstream locations in the Sacramento River during the growing season because little rainfall occurs. In addition, surface water bodies that receive rice field drainage waters, such as the Colusa Basin Drain, have the highest DOC concentrations of the Sacramento Valley watershed (Saleh et al., 2003; Chow et al., 2007) and flow directly into the Sacramento River. Other

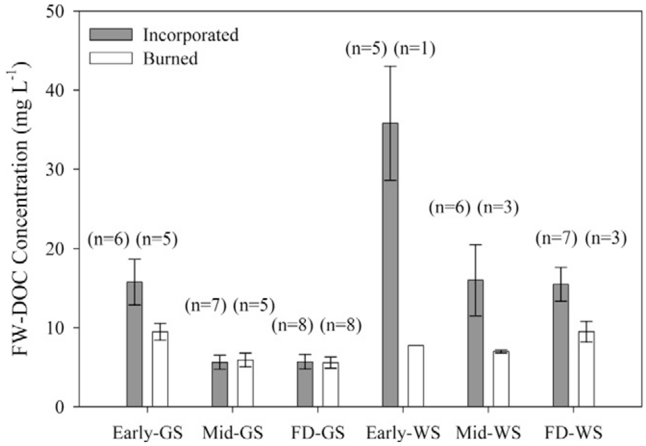

Fig. 3. Average subseason flow-weighted (FW) dissolved organic carbon (DOC) concentrations for incorporated and burned fields. Subseasons include: early growing season (Early-GS), mid-growing season maintenance flow (Mid-GS), final drain of growing season (FD-GS), early winter season (Early-WS), mid-winter season maintenance flow (Mid-WS), and final drain of winter season (FD-WS). Early-GS includes drainflow before pesticide application, draining of the field, or the first 30 d of drainflow. Mid-GS includes all remaining drainflow up to the final drain. Early-WS includes the first 30 d of maintenance flow and Mid-WS includes all remaining drainflow up to the final drain. Sample populations (*n*) are provided and error bars represent standard error.

organic compounds, such as pesticides used in rice production, have the ability to be transported across the same distance (Orlando and Kuivila, 2004, Finlayson et al., 1993). However, it should be noted that rice fields are not the sole potential source of DOC in the Sacramento Valley, as there are many wetlands in the region, which are known to increase DOC concentration in surface waters (Díaz et al., 2008). Wetlands have been shown to have a large impact on watershed level DOC flux, as positive linear relationships between wetland area and DOC flux have been determined (e.g., Laudon et al., 2004). In addition, urban areas can impact DOC in streamwater; Sickman et al. (2007) determined that urban runoff accounted for 17% of the DOC flux in the Sacramento River.

Dissolved Organic Carbon and the Terrestrial Carbon Budget

The seasonal fluxes of DOC with drainage water represented only a small portion of the terrestrial C pool in rice systems. Average annual DOC losses per site represented 0.22% of the soil organic carbon in the upper 15 cm (assuming a bulk density of 1.2 g cm^{-3}). Among straw incorporated fields, DOC losses via drainflow represented between 0 and 3.8% of the rice straw C in WS-2006 and between 0.3 and 1.9% in the WS of 2007. As a C export pathway, drainage waters were small in comparison to C loss via grain removal (2.4 to 5.5 Mg ha^{-1}, based on yields in Table 2 and a C concentration of 41%) and annual heterotrophic carbon dioxide (CO_2)-C fluxes (2.4 Mg ha^{-1}; McMillan et al., 2007), but were similar to methane (CH_4)-C fluxes in nonflooded burned fields (13–50 kg ha^{-1}) and in flooded, straw-incorporated fields (98–205 kg ha^{-1}; Fitzgerald et al., 2000). It

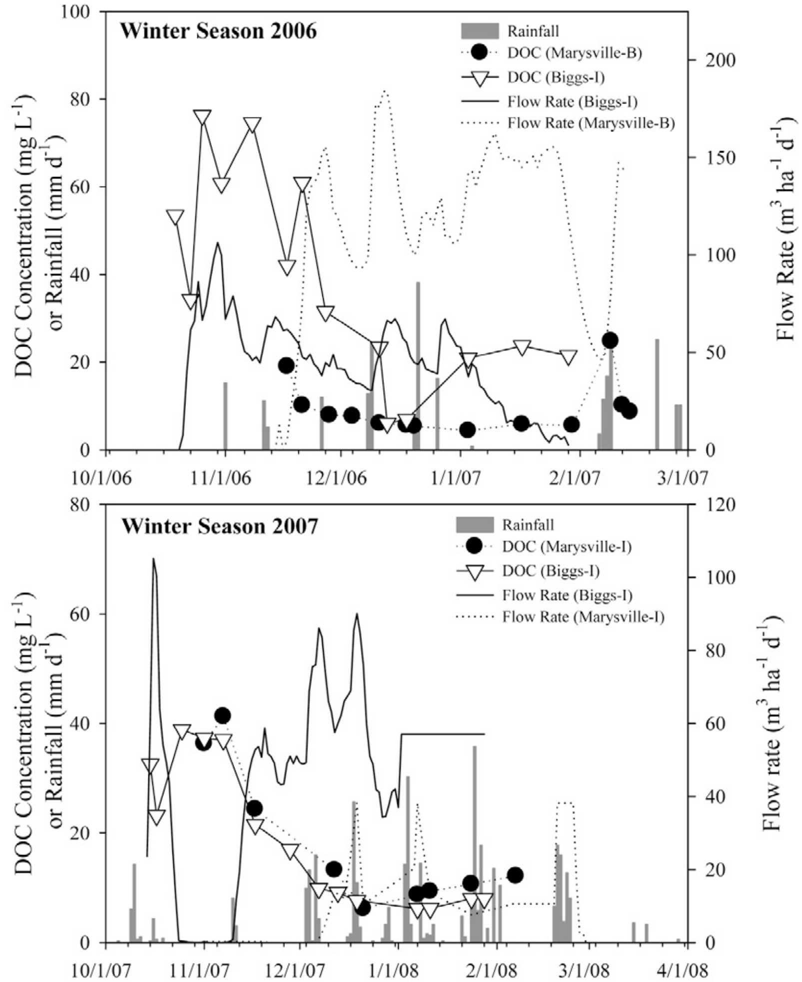

Fig. 4. Dissolved organic carbon (DOC) concentrations in outflow from two representative fields during maintenance flow in winter season 2006 and winter season 2007. I = incorporated; B = burned.

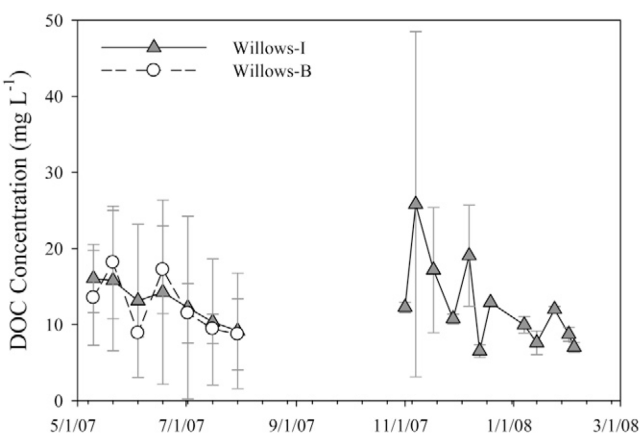

Fig. 5. Dissolved organic carbon (DOC) concentrations from samples collected in-field at Willows during the growing season and winter season of 2007. Error bars represent standard deviation. I = straw incorporation, B = burning.

appears that in incorporated fields with high rates of maintenance flow (e.g. Biggs-I) winter losses of C as DOC could even exceed CH_4–C losses (Table 3).

Water management affected whether rice productions systems were net importers or exporters of DOC during the growing season. After estimating seasonal water inflows as the sum of outflow and evapotranspiration (9200 m^3 ha^{-1}; Lourence and Pruitt, 1971) and estimating growing season influx using average seasonal DOC concentrations in supply canals, rice fields received more DOC than they exported during the growing season. Based on this simple calculation of inflow, which does not account for percolation losses, the average growing season net import of DOC was 13 kg ha^{-1}. Other surface irrigation systems in California have also been shown to result in a similar net import of DOC to the system (21.4 kg ha^{-1}; Poch et al., 2006). Without reliable estimates for evaporation during winter flooding, a winter season dissolved C budget is difficult to discern. Using the evapotranspiration that Lourence and Pruitt (1971) measured in September (1460 m^3 ha^{-1}), and assuming a 4-mo flooding period, provides a total winter season evaporation estimate of 5840 m^3 ha^{-1}. Based on this estimation and averaged across all fields, winter flooding resulted in a net export of DOC (42 kg ha^{-1}), although at two fields, net imports were estimated. McMillan et al. (2007) measured an annual net C influx to rice systems of 670 kg ha^{-1} and Kroodsma and Field (2006) determined that California rice fields sequester 550 kg ha^{-1} yr^{-1}, but dissolved C fluxes were not considered in either calculation. Winter flooding on straw-incorporated fields, when managed with MF can result in a net export of 180 kg ha^{-1} of DOC (Biggs-I in 2006). Our results suggest that future research on California's agricultural systems should consider the dissolved C components when assessing whether production systems are a net source or sink of C.

Dissolved Organic Carbon and Water Management

Subseasonal dynamics of DOC concentrations in rice field outflows were affected by straw management and the timing of water operations. During the winter season, straw-incorporation increased DOC losses over burning, but outflow accounted for 88% of the variability in DOC loss among all fields. Winter outflow was also a strong predictor of TDS flux. Water flux has also been shown to be the driving factor of DOC loss from other agricultural systems (Ruark et al., 2009; Brye et al., 2001) as well as agriculturally dominated watersheds (Dalzell et al., 2007). Dalzell et al. (2007) also suggest that a strong relationship between water flux and DOC flux is a common trait of managed landscapes. During the growing season, a significant dilution effect was determined; greater amounts of outflow diluted seasonal FW-DOC concentrations. During the winter season, a dilution effect was not determined; greater amounts of outflow did not dilute seasonal FW-DOC concentrations. However, during the winter season, DOC concentrations clearly decrease over time (Fig. 4), suggesting that DOC is immediately available for loss after straw incorporation and that large amounts of DOC can get flushed out of the system at the onset of outflow. Also, DOC concentrations appear to be affected by changes in daily flow rate or occurrence of rainfall (Fig. 3), although more intensive sampling is required to better understand these relationships.

The DOC concentrations decreased in flooded fields when no outflow occurred (Fig. 5). Delaying the onset of outflow may provide a large benefit in reducing DOC concentrations in outflow. Holding water during October and November would reduce the DOC concentrations in outflow, but other tradeoffs such as straw decomposition rates and greenhouse gas fluxes, would need to be assessed. In addition, the mechanism for the decrease in DOC concentration is unknown. Several processes can cause the removal of DOC in these systems including microbial utilization, photochemical oxidation, and flocculation and settling of particles. Further research is required to assess if the reduction in DOC concentration in low-flow irrigation management conserves the organic C in the terrestrial system or increases C losses through other pathways.

Conclusions

Straw incorporation and winter flooding of rice fields have added a new flux of DOC and TDS into Sacramento Valley surface waterways over the past 15 yr. Based on our data, it is evident that the export of DOC from these fields can contribute to increased DOC concentrations in the Sacramento River, but rice fields may not be the cause of peak DOC concentrations typically observed later in the winter season. Further

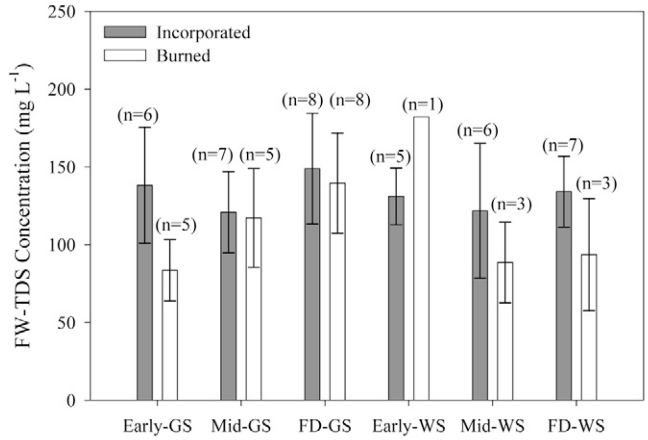

Fig. 6. Average subseason flow-weighted (FW) dissolved organic carbon (TDS) concentrations for incorporated and burned fields. Subseasons include: early growing season (Early-GS), mid-growing season maintenance flow (Mid-GS), final drain of growing season (FD-GS), early winter season (Early-WS), mid-winter season maintenance flow (Mid-WS), and final drain of winter season (FD-WS). Early-GS includes either discrete drainflow events in April through June or the first 30 d of drainflow. Mid-GS includes all remaining drainflow up to the final drain. Early-WS includes the first 30 d of maintenance flow. Sample populations (*n*) are provided and error bars represent standard error.

investigation into quality components of DOC is required to fully address this issue. Rice field outlet water rarely exceeded drinking water standards for TDS and therefore would not be considered a source for this potential contaminant. Reduction in DOC concentrations from rice outlets may be achieved through changes in water management, but environmental and agronomic trade-offs need to be fully explored. Such changes in water management may need to be considered in parts of the world where rice production is extensive and surface waters are used as the main drinking water source.

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