Published September 9, 2014

Journal of Environmental Quality

TECHNICAL REPORTS

SURFACE WATER QUALITY

Nutrients and Sediments in Surface Runoff Water from Direct-Seeded Rice Fields: Implications for Nutrient Budgets and Water Quality

Bruce A. Linquist,* Matthew D. Ruark, Randall Mutters, Chris Greer, and Jim E. Hill

Abstract

Nutrient losses from rice fields can have economic and environmental consequences. Little is known about nutrient losses in surface runoff waters from direct-seeded rice systems, which are common in the United States and increasingly more so in Asia. The objectives of this research were to quantify nutrient losses from California rice fields in surface runoff waters and to determine when and under what conditions losses are greatest. Research was conducted in 10 rice fields varying in residue (burned or incorporated) and water management over a 2-yr period. Concentrations of NH_4–N and NO_3–N in runoff water across sites, seasons, and management practices averaged <0.1 mg N L^{-1}. Runoff water PO_4–P concentration averaged 0.14 mg L^{-1} and was not affected by season or straw management practices. However, P fluxes were higher in the winter when rice straw was burned (2.59 kg ha^{-1}) as opposed to incorporated (0.44 kg ha^{-1}). Average seasonal runoff water K concentrations did not vary with season and straw management, although they were highest at the onset of the winter season. Average total suspended solids (TSS) concentrations did not vary by season but were highest during the winter in the straw-incorporated fields (46 mg L^{-1}). Rice fields were sinks for K (4.9 kg K ha^{-1}) during the growing season. Fields were not significant sources of nutrients or TSS during the growing season; however, during the winter fallow they could be sources of NH_4–N, P, K, and TSS, especially as water fluxes from fields increased.

Agricultural intensification, whereby yields per unit area are increased, is required to meet future food demand. However, such intensification can result in negative environmental consequences, such as nonpoint-source pollution (Matson et al., 1997; Tilman, 1999). Therefore, sustainable intensification whereby the aforementioned objective is achieved at minimal or reduced environmental cost is required (Godfray et al., 2011; Cassman et al., 2003). Nutrient pollution from agriculture is a major cause of poor water quality (Buckley and Carney, 2013). Nutrient losses can also be an economic concern for farmers because fertilizer costs have increased by 180 to 273% (depending on fertilizer) since 2000 (USDA, 2013) and nutrient losses in surface runoff can be high, representing a significant portion of that applied (Zhao et al., 2012; Krupa et al., 2011; McDowell et al., 2001). However, in some cases, such as P, the amount of nutrient lost in surface runoff maybe agronomically insignificant, but water quality may be impaired because eutrophication can occur at low water P concentrations (Hart et al., 2004).

In rice systems, N losses can occur via leaching, gaseous losses, and surface water runoff. Although rice systems are flooded for the majority of the growing season, leaching is considered to be a minor loss mechanism due to the impermeability of most soils and high denitrification potential (Liang et al., 2014; Buresh et al., 2008; Bouman et al., 2002). For N, the main loss pathways are due to gaseous loss via NH_3 volatilization and denitrification (Buresh et al., 2008). Nitrogen losses in surface runoff waters can also be high. Zhao et al. (2012) reported mineral N losses of 2 to 22 kg N ha^{-1} during a single rice growing season. Many studies suggest that P runoff losses are minimal and agronomically insignificant in rice systems; however, under conditions where there is runoff shortly after application, elevated P levels in surface water can be a concern (Lundy et al., 2012; Zhang et al., 2004). Potassium, which is not considered a water pollutant, is mobile in the surface water and can be transported down the field in the irrigation water (Simmonds et al., 2013). Krupa et al. (2011) reported that

J. Environ. Qual. 43:1725–1735 (2014)
doi:10.2134/jeq2014.03.0135
Received 27 Mar. 2014.
*Corresponding author (balinquist@ucdavis.edu).

B.A. Linquist and J.E. Hill, Dep. of Plant Sciences, Univ. of California, One Shields Ave., Davis, CA 95616; M.D. Ruark, Dep. of Soil Science, Univ. of Wisconsin, 1525 Observatory Dr., Madison, WI 53706; R. Mutters, Univ. of California Cooperative Extension, 2279B del Oro Ave., Oroville, CA 95965; C. Greer, Univ. of California Cooperative Extension, 142 Garden Hwy., Suite A, Yuba City, CA 95991. Assigned to Associate Editor Hailin Zhang.

Abbreviations: TSS, total suspended solids.

during the growing season the amount of dissolved K exported from rice field runoff water was >8 kg ha^{-1}, which was much greater than export of dissolved mineral N or PO_4–P (1.0 and 0.32 kg ha^{-1}, respectively). Potassium is also susceptible to runoff losses during the winter fallow because up to 80% of K in rice straw is washed out during this period (Bakker and Jenkins, 2003) and can end up in the runoff water. Total suspended solids (TSS) in water is an important water quality indicator and is closely related to turbidity and to the ecological health of water ways. Some studies have found that rice systems are linked to high TSS in downstream waters (Poudel et al., 2013; Sanchez et al., 2012); however, rice management practices can help reduce sediment losses (Feagley et al., 1992).

In California's direct water-seeded rice systems, the seed bed is prepared and fertilizers are applied before the fields are flooded, and the seed flown in by airplane. Early in the season, water may be temporarily drained or lowered to facilitate establishment and herbicide applications. The field remains flooded until about 1 mo before harvest, when it is drained to allow the soil to dry for harvest. In California, before the mid-1990s straw was burned and the fields were left unflooded in the winter; however, due to the Rice Straw Burning Reduction Act of 1991 (AB 1378), straw burning was phased out to allow a maximum of 25% of acreage to be burned. Currently, about 12% of rice area is burned annually (CRC, 2013), a small percentage of the straw is baled, and the majority of growers incorporate the rice straw and either intentionally flood or let winter rains naturally flood the field to facilitate straw decomposition (Linquist et al., 2006). During the winter fallow period, intentional flooding and/or rainfall may lead to runoff if the flood water is not contained within the field. Nutrient losses and their impacts on nutrient budgets and water quality have not been examined in these systems. Most studies that have evaluated nutrient loss were conducted during the growing season, and the majority of these were in Asia, where cultural practices are different from those in California. Typically in Asia, rice is transplanted and fertilizers are applied into flooded water; however, the general trend in Asian rice systems is toward direct seeding (Rao et al., 2007). In direct water-seeded systems such as those found in California, much of the fertilizer N is injected into the soil as aqua-NH_3 before planting (Linquist et al., 2009). Some N and the P and K fertilizers are usually applied to the soil surface at the same time and may or may not be incorporated into the surface soil. Therefore, to better understand nutrient losses from direct water-seeded rice fields, our objectives were (i) to quantify nutrient (N, P, and K) and TSS losses from rice fields in runoff water, (ii) to determine when losses are greatest, and (iii) to determine how nutrient loss is related to winter fallow straw management and water flux in direct water-seeded rice systems in California.

Materials and Methods

Study Site Characteristics and Management Practices

This study was conducted on rice grower fields in California's Sacramento Valley from April 2006 through March 2008. The cooperating grower sites were located near Marysville, Biggs, Arbuckle, and Willows (Fig. 1) and represented typical soils and farming practices in the region (Tables 1 and 2). At each site, two fields of varying straw management (incorporated [I] or burned [B]) were identified. Each field varied with respect to overall water management during the growing (1 Apr.–30 Sept.) and winter (1 Oct.–30 Mar.) seasons (Table 2). Management details are provided by Ruark et al. (2010), but a brief summary follows. Early in the growing season, water management varied among growers due to variability in pesticide management, with some fields being drained and others stopping inflow and/or runoff around the time of application; however, after pesticide applications and required water hold times, most fields were managed with maintenance flow, where a continuous flow of water through the field was maintained to establish a consistent depth of water in the field. Some growers did not have any water runoff and instead managed flood water depth by regulating water input. In the winter season, straw-incorporated fields (with the exception of Arbuckle-I in 2006) were flooded between October and February. Water was managed with maintenance flow for most fields where straw was incorporated (Table 2). In fields where rice straw was burned, irrigation water was not used to flood the field; however, in some burned fields the outlets were blocked, allowing rainfall to flood the field. An exception is the Marysville-B site, which, despite being burned, was also flooded

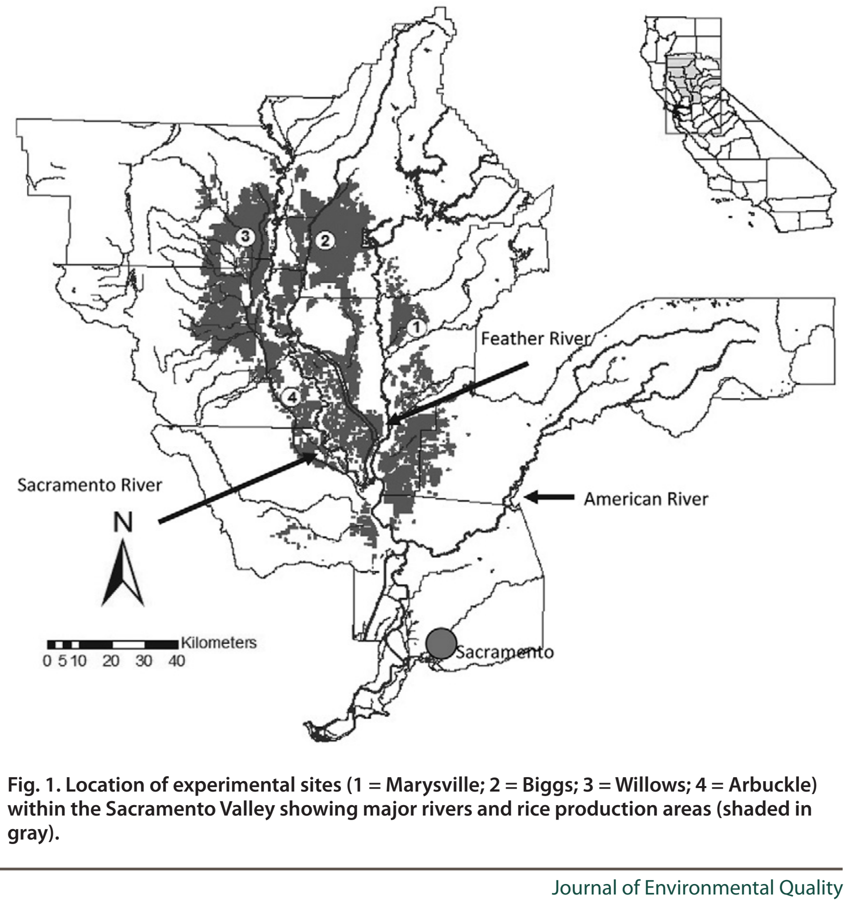


Fig. 1. Location of experimental sites (1 = Marysville; 2 = Biggs; 3 = Willows; 4 = Arbuckle) within the Sacramento Valley showing major rivers and rice production areas (shaded in gray).

Table 1. Field sizes, soil classification, and soil characteristics, including pH, cation exchange capacity, soil organic carbon, and texture of the 10 rice fields in the Sacramento Valley used in this study.

Field	Location	Size	Soil classification†	pH	CEC‡	SOC§	Total N	Olsen- P	Extractable K	Sand	Clay
		ha			$cmol_c$ kg^{-1}	g kg^{-1}				%	
1	Marysville	25.9	fine, mixed, active, thermic, Abruptic Durixeralf	4.8	14.2	9.3	0.8	22.3	65.3	37.5	27.5
2	Marysville	24.3	fine, mixed, active, thermic, Abruptic Durixeralf	4.8	16.5	9.3	0.9	15.1	32.5	35.5	35.3
3	Marysville	9.3	fine-loamy, mixed, active, thermic Aquic Haploxerepts; fine, mixed, active, thermic Abruptic Durixeralf	4.8	14.1	11.2	na¶	25.7	na	41.0	20.0
4	Biggs	42.1	very fine, smectitic, thermic Xeric Epiaquert; very fine, smectitic, thermic Xeric Duraquert	5.0	52.7	11.1	1.35	5.2	168.9	12.0	63.3
5	Biggs	57.9	very fine, smectitic, thermic Xeric Epiaquert; very-fine, smectitic, thermic Xeric Duraquert	5.2	52.0	12.1	1.45	9.2	181.5	15.8	60.3
6	Arbuckle	52.2	fine, smectitic, thermic Xeric Endoaquert	6.0	53.0	15.4	1.70	6.3	188.3	8.4	56.3
7	Arbuckle	58.7	fine, smectitic, thermic Xeric Endoaquert	6.2	49.5	13.1	1.50	11.2	203.3	7.0	54.0
8	Arbuckle	68.0	fine, smectitic, thermic Xeric Endoaquert	6.0	52.6	13.9	1.65	9.1	189.0	8.8	53.5
9	Willows	45.3	fine, smectitic, thermic, Sodic Endoaquert	5.8	38.1	17.0	1.88	14.3	237.8	16.8	41.0
10	Willows	32.4	fine, smectitic, thermic, Sodic Endoaquert fine, smectitic, thermic Typic Haploxererts	5.8	32.3	18.1	1.75	9.9	150.9	22.4	37.1

† Representing >75% of the soil area within the field.

‡ Cation exchange capacity.

§ Soil organic carbon.

¶ Not available.

during the 2006 winter to create waterfowl habitat. There was also runoff water from unflooded fields after some rainfall events.

After the 2006 growing season, 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 2006 growing season was burned (becoming Marysville-B), and a new straw-incorporated site was identified. Before the 2007 winter, Marysville-B and Willows-B could not be burned due to unfavorable weather conditions. No new burned fields were identified at Marysville and Willows for the 2007 winter. The field that had been Marysville-B for the 2007 growing season was identified as the straw-incorporated field for the 2007 winter season.

In terms of fertility management, the rates used by growers in this study are typical for California (Linquist et al., 2009), with higher N rates being used for medium-grain rice varieties (M205 and M206) and lower rates for specialty varieties (Koshihikari) that are susceptible to lodging (Table 2). All fertilizers were applied before flooding and planting. In all fields, most of the N was injected as aqua-ammonia, and the remainder was broadcast or sprayed on the surface (sometimes being left on the surface and other times lightly raked in along with P and K fertilizer). Phosphorus and K were applied in all fields except fields 6, 7, and 8.

Water Sampling and Analysis

Each field had one or two irrigation water inlets and one water outlet that drained water into drainage canals. Runoff was measured by installing a rectangular weir fitted with a Global-Water pressure sensor/data logger 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 when they malfunctioned. For the 2006 growing season, runoff was measured entirely 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 or 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 2–11 ha), and water depth was recorded before and after the drain. Early growing season and end-of-winter season drain volumes were 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.

Water samples were collected from the field inlets and outlets. Samples were collected on a weekly or biweekly basis, with more intensive sampling conducted after the onset of maintenance flow, 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 analyses could be performed. Water samples were analyzed for NH_4–N and NO_3–N (Doane and Horwath, 2003), PO_4–P (hereafter referred to as water P concentrations) using the ascorbic acid molybdenum blue method modified from Murphy and Riley (1962) with a lower detectable limit of 0.01 mg P L^{-1}

Table 2. Agronomic and water management practices of 10 rice fields in the Sacramento Valley.

Field	Site	Trt†	Yield	Fertilizer rate (N-P-K)	Planting date	Variety	Flood date	Water management‡		Drain date§	Trt	Flood date	Water management¶	Drain date
								Early	Mid					
			Mg ha^{-1}	kg ha^{-1}										
					2006 growing season						2006 winter season			
1	Marysville	I	6.5	90–28–54	26 May	Koshihikari	22 May	F	MF	6 Sept.	B	14 Nov.	F	14 Feb.
2	Marysville	B	7.6	90–28–54	11 May	Koshihikari	7 May	F	MF	31 Aug.	–	–	–	–
3	Marysville	–	–	–	–	–	–	–	–	–	I	11 Nov.	F	14 Feb.
4	Biggs	I	13.3	185–17–26	15 May	M202	12 May	F	MF	3 Sept.	I	21 Oct.	F	29 Jan.
5	Biggs	B	11.0	185–17–26	8 May	M206	8 May	F	MF	21 Aug.	B		RF	none
6	Arbuckle	I	11.6	185–0-0	12 May	M206	12 May	F	MF	22 Aug.	–	–	–	–
7	Arbuckle	–	–	–	–	–	–	–	–	–	I		NF	none
8	Arbuckle	B	12.9	185–0–0	11 May	M206	11 May	F	MF	22 Aug.	B		NF	none
9	Willows	I	na	177–17–31	14 May	M204	14 May	FH	MF	7 Sept.	I	8 Nov.	F	1 Feb.
10	Willows	B	11.0	177–17–31	25 May	M205	25 May	FH	MF	14 Sept.	B		NF	none
					2007 growing season						2007 winter season			
1	Marysville	B	5.8	90–28–54	22 May	Koshikihari	17 May	FH	FH	12 Sept.	I	20 Oct.	F	20 Feb.
2	Marysville	–	–	–	–	–	–	–	–	–	–	–	–	–
3	Marysville	I	7.2	90–28–54	26 May	Koshikihari	21 May	F	MF	12 Sept.	B		NF	none
4	Biggs	I	12.4	185–17–26	24 Apr.	M206	20 Apr.	F	MF	10 Aug.	I	8 Oct.	F	28 Jan.
5	Biggs	B	13.5	185–17–26	16 Apr.	M205	13 Apr.	F	MF	13 Aug.	B		RF	none
6	Arbuckle	–	–	–	–	–	–	–	–	–	–	–	–	–
7	Arbuckle	I	11.9	185–0–0	27 Apr.	M202	27 Apr.	F	MF	21 Aug.	I	26 Nov.	F	5 Feb.
8	Arbuckle	B	12.6	185–0–0	28 Apr.	M206	27 Apr.	F	FH	21 Aug.	B		RF	8 Feb.
9	Willows	I	11.7	177–17–31	30 Apr.	M205	24 Apr.	FH	FH	27 Aug.	I	12 Oct.	F	15 Feb.
10	Willows	B	11.2	177–17–31	30 Apr.	M205	24 Apr.	FH	FH	27 Aug.	B		RF	none

† Treatments are straw incorporated (I) or burned (B), which all occur after the harvest in the fall.

‡ Early water management practices during the growing season include flood with water allowed to flow through or drained for herbicide applications (F) or water held (FH). Midgrowing season water management practices include maintenance flow (MF) or holding (FH). Water samples were taken from all fields at the final drain but were not taken if the field water was held earlier in the season (FH).

§ Date when boards blocking the outlet were removed to allow field to drain; "none" indicates there was no standing water in the field to drain.

¶ Winter water management practices include flooding (F), flooding due to rainfall (RF), or no flooding (NF). For the RF management, outflow occurred as surface runoff. No samples were collected from NF fields.

(APHA, 1999), and K (USEPA, 2001). Total suspended solids were determined as the change in weight of filter paper before and after filtering (APHA, 1998).

During the growing season, three subseasons were identified: early season, midseason, and the final drain. During the early season, runoff varied among fields due to how water was managed during establishment and pesticide applications. During the midseason, there was runoff due to maintenance flow in most fields, although in some fields there was no runoff. The final drain was when the field was drained in preparation for harvest. Similarly, the winter season was divided into three subseasons: early winter season, midwinter season, and the final drain.

Seasonal fluxes (kg ha^{-1} per season) of each nutrient 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 runoff occurring between days that are midway between each sampling date. Flow-weighted nutrient concentrations were calculated for each season and subseason by dividing the total solute flux by the total water flux of each period.

Seasonal net loads for each nutrient were estimated by subtracting runoff fluxes from input fluxes. To estimate nutrient input fluxes, irrigation water inputs were estimated using the following equation:

$$\text{Irrigation water inputs} = \text{runoff} + \text{evapotranspiration} + \text{percolation} - \text{rainfall}$$

Runoff from each field was measured directly as described above. Growing season evapotranspiration was 11,500 m^3 ha^{-1}, which is considered average for California (Hill et al., 2006). Losses due to percolation are minimal in California rice fields due to the practically impermeable plow layer. Liang et al. (2014) measured hydraulic conductivity on a number of California rice soils below the root zone and reported the average hydraulic conductivity of typical rice fields to be 0.032 cm d^{-1}. This factor was multiplied by the number of days each field was flooded to estimate percolation losses. Rainfall data were collected by the University of California Integrated Pest Management Program, and the rainfall monitoring stations were within 15 km of each corresponding field site.

Yields from each field and year are reported in Ruark et al. (2010). Soil samples (0–15 cm depth, 6 cm in diameter) were collected from each field 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; Kalra, 1995), cation exchange capacity (Rible and Quick, 1960), total carbon (AOAC, 1997), soil organic C (Nelson and Sommers, 1982), Olsen-P (Olsen and Sommers, 1982), extractable K (1 mol L^{-1}) NH_4OAC (Sparks 1996), and texture (Sheldrick and Wang, 1993).

Data Analysis

Average seasonal flow-weighted nutrient concentration and total seasonal nutrient fluxes were subjected to ANOVA. When analyzing nutrient flux data from fields, some fields had no runoff water during the winter (for reasons discussed above), and these were not included in the analysis. All data parameters were subjected to normality test using the Shapiro-Wilk approach (P = 0.521 to <0.0001); data that failed the normality test were analyzed in log-transformed forms (SAS Institute, 2010). Differences in measured parameters between type of straw management were determined using PROC MIXED for unbalanced tests with adjusted Tukey-Kramer for multiple treatment mean comparisons at P < 0.05 (SAS Institute, 2010). The main effects due to straw management and interaction and random effects of year, site, season and blocking were analyzed using PROC MIXED covariance test (SAS Institute, 2010). Analysis of covariates was performed on a randomized complete block, blocked split plot design with straw management as the main plot treatment, site as block effect, and year and season as the split block and treatment effects, respectively. Initial analyses showed that year effect was not a significant covariate in the model; hence, the year effect was removed in the final model.

Results and Discussion

Nutrient and Total Suspended Solids Concentrations of Irrigation Water

The inorganic N (NO_3–N and NH_4–N) concentrations of the incoming irrigation water were low (range, 0.01–0.26 mg L^{-1}), with little difference between locations and seasons (Table 3), although the Willows irrigation water had higher and more variable NO_3–N concentrations than the other sites. Similar observations were made for P concentrations, which averaged ≤0.10 mg L^{-1}. In contrast, K concentrations did not vary substantially between seasons but did vary by location. The Marysville location, which receives irrigation from the Yuba River, had the lowest K concentrations, followed by Biggs (Feather River) and then by Arbuckle and Willows, which receive water from the Sacramento River. Irrigation TSS also varied by location, with Marysville and Biggs having lower TSS concentrations than the two sites receiving Sacramento River water.

Seasonal Water Fluxes

Seasonal water runoff flux amounts during the growing and winter seasons, averaged across sites and years, were 2250 and 3300 m^3 ha^{-1}, respectively, but with considerable variation. During the growing season, runoff fluxes ranged from 300 to 4720 m^3 ha^{-1} (Table 4). Low runoff was associated with fields where there was no maintenance flow during the midseason, and all of the runoff occurred either when fields were drained for herbicide application or at the end of the season. During the winter, runoff was even more variable (0–13,060 m^3 ha^{-1}) because some fields were not flooded and some had very high flow rates. Rainfall resulted in runoff from some fields that were not intentionally flooded. Averaged across locations, rainfall during the 2006–2007 winter was less than half of what was received during the 2007–2008 winter (209 vs. 424 mm) (Ruark et al., 2010); thus, during the 2007–2008 winter there were more fields with runoff than in 2006–2007.

Nutrient and Total Suspended Solids Concentrations and Fluxes of Runoff Water

Nitrogen

Average seasonal NO_3–N concentrations in field runoff water were not affected by straw management but were higher in the winter than during the growing season (0.05 vs. 0.02 mg L^{-1}) (Table 5). Concentrations of NO_3–N were higher at the onset of both the growing and winter seasons and lowest at the end of each season during drainage (Fig. 2). The NO_3–N flux in runoff water was low, averaging 0.09 kg ha^{-1} in the growing season and 0.24 kg ha^{-1} in the winter (Table 5), for a total annual flux of 0.33 kg ha^{-1} yr^{-1}.

Concentrations of NH_4–N in field runoff water were low and did not vary by season or straw management (Table 5). Across fields and years, seasonal NH_4–N averages ranged from 0.07 to 0.10 mg L^{-1} (Table 5) and changed little during the season (Fig. 2). On average, the annual NH_4–N flux in runoff water was 0.91 kg ha^{-1} yr^{-1} (0.31 kg ha^{-1} in growing season and 0.60 kg ha^{-1} in winter season) (Table 5).

Table 3. Average nutrient and total suspended solid concentrations of irrigation water for each site and season.

Location	NO_3–N	NH_4–N	PO_4–P	K	TSS†
	mg L^{-1}				
			Growing season		
Marysville	0.01 (0.01)‡	0.04 (0.06)	0.02 (0.02)	0.49 (0.07)	7.2 (12.8)
Biggs	0.01 (0.03)	0.05 (0.09)	0.02 (0.02)	0.79 (0.10)	13.0 (11.5)
Arbuckle	0.08 (0.08)	0.03 (0.04)	0.09 (0.05)	1.32 (0.16)	36.1 (16.2)
Willows	0.19 (0.12)	0.06 (0.13)	0.10 (0.08)	1.81 (0.40)	32.4 (61.7)
			Winter season		
Marysville	0.05 (0.09)	0.02 (0.02)	0.03 (0.04)	0.54 (0.12)	5.2 (12.5)
Biggs	0.05 (0.09)	0.02 (0.02)	0.02 (0.02)	0.94 (0.09)	6.8 (2.8)
Arbuckle	0.07 (0.11)	0.04 (0.03)	0.03 (0.02)	1.77 (0.14)	20.2 (7.1)
Willows	0.26 (0.37)	0.01 (0.01)	0.05 (0.05)	1.61 (0.16)	14.7 (8.2)

† Total suspended solids.

‡ Data are averages for all sampling events in 2006 and 2007 with SD in parentheses.

The growing season N concentrations reported here were similar to those reported by Krupa et al. (2011) based on a watershed study in California. Similar to findings by Krupa et al. (2011), we found no within-season variation in runoff water NO_3–N concentrations. However, Krupa et al. (2011) found higher NH_4–N concentrations in July (0.12 mg L^{-1} compared with <0.06 for all other measurements), which they attributed to midseason top-dress N applications. Similarly, Zhao et al. (2012) reported that NH_4–N levels increase in runoff water after midseason N applications. However, in our study, midseason N applications were not applied to any of the fields. On a total mineral N basis (NO_3–N + NH_4–N), growing season N fluxes were 0.40 kg N ha^{-1}, and during the winter they were 0.84 kg N ha^{-1}. Mineral N discharge amounts were not affected by N rate as evidenced by the Marysville site, which had the lowest fertilizer N rates but had similar amounts of N in the runoff water to other sites. Krupa et al. (2011) reported a total growing season mineral N flux of 1.02 kg N ha^{-1}, which is similar to our findings but much lower than reported in some Asian studies. For example, Zhao et al. (2012) found seasonal fluxes of NO_3–N in runoff water ranging from 0.41 to 9.6 kg N ha^{-1} and from 0.77 to 13.2 kg N ha^{-1} NH_4–N. Also, Yoon et al. (2006) reported NO_3–N concentrations from a study in Korea that were higher than we found in this study (range, 1–3.5 mg N L^{-1}) and NH_4–N ranging from 1 to 12 mg N L^{-1}. In China, Tian et al. (2007) reported values up to 8 mg N L^{-1} for NO_3–N and 4 mg N L^{-1} for NH_4–N. There are several possible reasons for the low fluxes and concentrations of N in runoff water in this study compared with other studies. First, N fertilizers in California rice systems are mostly incorporated into the soil before flooding. In the Yoon et al. (2006) study, N was applied in three split applications and broadcast into the water. Zhao et al. (2012) found that the amount of N in runoff water was associated with the timing of N application in relation to rainfall. When N was applied into the flood water just before or during a rainfall event, N flux increased in runoff waters. Second, the irrigation water used in our study was low in NO_3–N and NH_4–N (Table 3). In contrast, Tian et al. (2007) reported that NO_3–N and NH_4–N concentrations in their irrigation water were 1.03 and 0.54 mg L^{-1}, respectively.

Table 4. Seasonal water and nutrient fluxes of 10 rice fields in the Sacramento Valley.

Field	Location†	Growing season 2006					Winter season 2006					Growing season 2007					Winter season 2007				
		Water	NO_3	NH_4	P	K	Water	NO_3	NH_4	P	K	Water	NO_3	NH_4	P	K	Water	NO_3	NH_4	P	K
		m^3 ha^{-1}	——— kg ha^{-1} ———				m^3 ha^{-1}	— kg ha^{-1} —				m^3 ha^{-1}	——— kg ha^{-1} ———				m^3 ha^{-1}	——— kg ha^{-1} ———			
1	M	2020	0.02	0.63	0.09	6.2	***13,060‡***	***1.2***	***3.5***	***10***	***110***	***430***	***0.00***	***0.02***	***0.00***	***1.3***	2270	0.12	0.20	0.08	4.9
2	M	***4640***	***0.03***	***0.04***	***0.13***	***1.5***	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
3	M	–	–	–	–	–	900	0.03	0.11	0.26	6.8	800	0.00	0.01	0.02	0.81	***0***	***0***	***0***	***0***	***0***
4	B	4720	1.2	0.25	0.47	6.2	6,160	0.19	0.90	2.7	38	3350	0.03	1.6	0.06	1.4	8360	0.47	0.77	0.08	18.4
5	B	***3140***	***0.05***	***0.11***	***0.38***	***3.8***	***60***	***0.00***	***0.00***	***0.00***	***0.15***	***4540***	***0.25***	***0.42***	***0.07***	***4.4***	***240***	***0.08***	***0.01***	***0.01***	***0.66***
6	A	2290	0.51	0.63	0.45	3.9	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
7	A	–	–	–	–	–	0	0	0	0	0	2550	0.04	0.43	0.08	2.9	1570	0.08	0.23	0.14	2.7
8	A	***3270***	***0.20***	***0.24***	***1.79***	***7.8***	***0***	***0***	***0***	***0***	***0***	***750***	***0.01***	***0.02***	***0.05***	***1.1***	***1100***	***0.05***	***0.13***	***0.26***	***3.5***
9	W	1290	0.04	0.46	0.16	3.2	680	0.13	0.03	0.20	4.0	1240	0.01	0.01	0.01	2.4	1300	0.02	0.03	0.03	4.8
10	W	***300***	***na§***	***0.08***	***0.04***	***0.45***	***0***	–	–	–	–	***640***	***0.01***	***0.01***	***0.03***	***1.3***	***1981***	***0.02***	***0.07***	***0.01***	***6.9***

† A, Arbuckle; B, Biggs; M, Marysville; W, Willows.

‡ Numbers in bold italics in the growing season represent fields that were burned the previous fall; numbers in italics in the winter season represent fields that were burned.

§ Not available.

Table 5. Mean seasonal nutrient and total suspended solid fluxes and flow-weighted concentrations as affected by straw management.

	Straw management	NO_3–N		NH_4–N		PO_4–P		K		TSS†	
		Flux	FW conc‡	Flux	FW conc	Flux	FW conc	Flux	FW conc	Flux	FW conc
		kg ha^{-1}	mg L^{-1}	kg ha^{-1}	mg L^{-1}	kg ha^{-1}	mg L^{-1}	kg ha^{-1}	mg L^{-1}	kg ha^{-1}	mg L^{-1}
Growing season	incorporated	0.11	0.03	0.50	0.10	0.17c	0.09	3.36b	1.36	114	35ab
	burned	0.07	0.02	0.12	0.05	0.31bc	0.11	2.70b	1.05	91	28ab
Winter season	incorporated	0.13	0.04	0.29	0.09	0.44b	0.14	10.86b	4.99	136	46a
	burned	0.34	0.06	0.91	0.07	2.59a	0.23	28.49a	2.55	247	19b
ANOVA§											
Year		ns	ns	ns	0.041	0.017	0.009	0.028	ns	ns	ns
Straw management		ns	ns	ns	ns	ns	ns	ns	ns	ns	0.042
Site		ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Season × site		0.029	ns	ns	ns	<0.0001	ns	<0.0001	ns	ns	ns
Season		0.017	ns	ns	ns	<0.0001	ns	<0.0001	ns	ns	ns
Season × straw management		ns	ns	ns	ns	<0.0001	ns	<0.0001	0.023	ns	0.0134

† Total suspended solids.

‡ Flow-weighted concentration.

§ For the ANOVA results only effects that are significant ($P \leq 0.05$) are shown. ns, not significant.

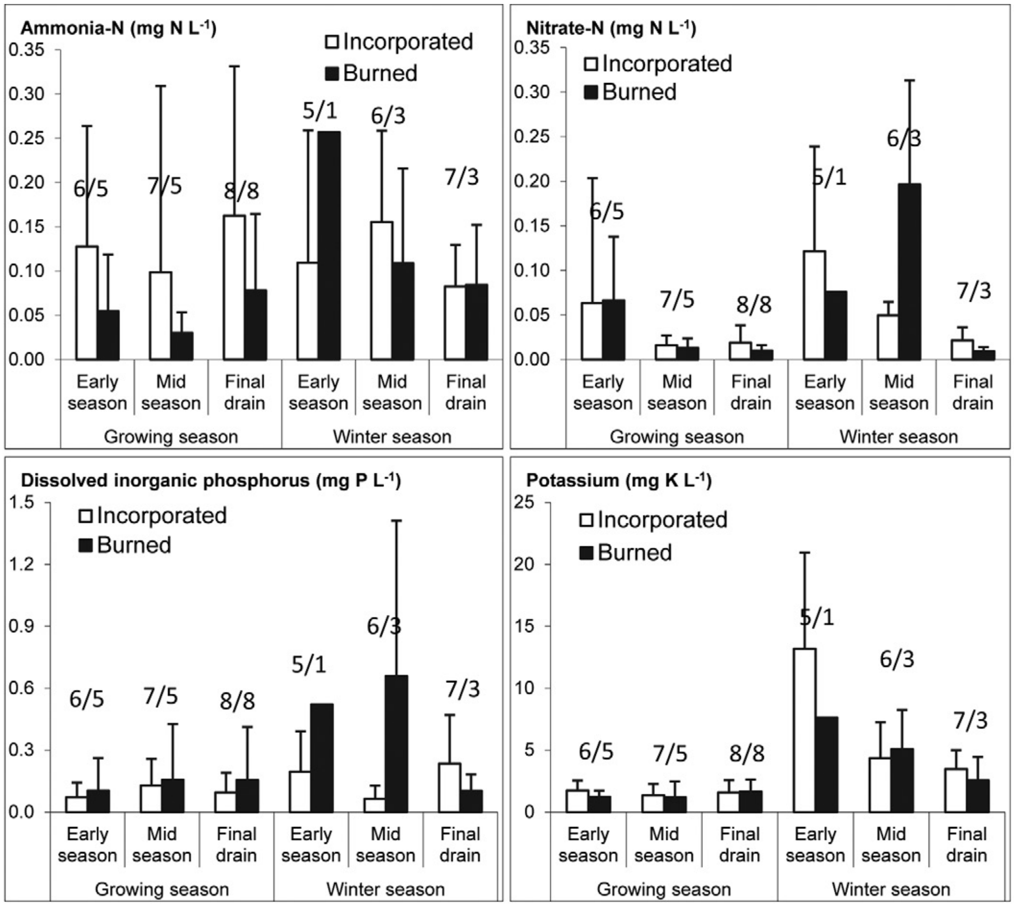


Fig. 2. Concentrations of NH_4–N, NO_3–N, PO_4–P, and K in water leaving rice fields for different sampling periods during the growing and winter seasons. Concentrations are averages across sites, years, and sampling period. The numbers above each bar are the sample population (*n*). Errors bars represent the SD of concentrations across sites, years, and sampling times within the specified sampling period.

Phosphorus

Runoff water PO_4–P concentration averages ranged from 0.09 to 0.23 mg L^{-1} and did not vary across seasons and straw management practices (Table 5). The PO_4–P concentrations in runoff water during the growing season are similar to previous reports for California rice systems (Krupa et al., 2011; Lundy et al., 2012). In all fields where P fertilizer was applied, it was applied before flooding to the soil surface. Application of P fertilizer 20 to 30 d after planting (instead of at planting) can reduce algae problems (Lundy et al., 2012; Spencer and Linquist, 2014). In these water-seeded systems, this P application is usually made into the flood water, and Lundy et al. (2012) found water P concentrations in excess of 1 mg P L^{-1} shortly after P was applied in such a way. To prevent P loss and contamination of offsite water, Lundy et al. (2012) prevented outflow from the field for 10 to 14 d, after which water P concentrations fell below 0.15 mg P L^{-1}. When P is applied before planting, Spencer and Linquist (2014) found that water P concentrations in the flood water could be reduced when the P fertilizer was tilled or raked into the soil surface.

Seasonal PO_4–P fluxes were lower in the growing season (average, 0.24 kg ha^{-1}) than in the winter (average, 1.52 kg ha^{-1}) (Table 5). Growing season runoff fluxes were not related to whether or not fertilizer P was applied: in fields 6, 7, and 8, where P was not applied, P in growing season runoff water averaged 0.23 kg P ha^{-1} (data not shown). During the winter, the seasonal PO_4–P fluxes were higher from fields where straw was burned (2.59 kg ha^{-1}) compared with where straw was incorporated (0.44 kg ha^{-1}). Also, concentrations of PO_4–P were highest during the early and midwinter season, especially in the burned fields (Fig. 2). Higher runoff fluxes during the winter may be due to several factors. First, winter P fluxes were found in burned fields. When residues are burned, there is little to no P loss via volatilization (Paul and Negi, 2008), but residue P is converted to extractable inorganic forms (Hogue and Inglett, 2012) that are more soluble and thus susceptible to runoff losses. Higher winter P fluxes could also be due to waterfowl defecation, which can lead to higher P loads (Olson et al., 2005; Kitchell et al., 1999). Rice fields in the Sacramento Valley serve as important waterfowl wintering areas in the Pacific Flyway, supporting up to 60% of the total flyway population (Central Valley Joint Venture, 2006). The total annual water bird count in the region has been estimated to be as high as 10 to 12 million (Gilmer et al., 1982).

There are no set water quality standards for P in California. The state of Wisconsin (WDNR, 2010) and the Republic of Korea (Kang et al., 2006) set thresholds at 0.10 mg P L^{-1} for surface waters. This threshold is the same as what we found for the average runoff water P concentration during the growing season and 0.09 mg P L^{-1} lower than average winter runoff P concentrations.

Phosphorus runoff problems in agriculture have usually been associated with overapplication of P fertilizer and manure resulting in high soil P levels; these areas are susceptible to P losses via leaching and surface runoff (Sharpley et al., 2001). The fields in this study did not have high soil P levels (Table 1); the fields with the highest P levels (Marysville) did not have high P fluxes (Table 4) and vice versa. Linquist et al. (2011) found that extractable soil P levels in conventionally managed California rice fields were lower than in organic rice fields or natural wetlands. They concluded that, by managing fertilizer P inputs to balance outputs, it is possible to maintain productivity while keeping soil P levels from increasing.

Potassium

Growing season runoff K concentrations averaged 1.21 mg K L^{-1} (Table 5), similar to that reported by Krupa et al. (2011) and lower than measured during the winter. During the winter, runoff K concentrations were not affected by straw management practices, but they did decline with time (Fig. 2). The lack of difference between burned and incorporated fields can be explained by the fact that water (from rainfall or flooding) readily leaches K out of the rice straw (Bakker and Jenkins, 2003), and K is soluble in water, similar to the K contained in ash after burning. Simmonds et al. (2013) found that K readily moves down field in the flow of irrigation water making it susceptible to runoff losses.

Fluxes of K from the field averaged 3.03 kg ha^{-1} during the growing season and 20 kg ha^{-1} during the winter (Table 5) but varied between fields, with fluxes ranging from <1 to 110 kg ha^{-1} depending on water flux (Table 4). Growing season K fluxes in water runoff from fields not fertilized with K were 3.9 kg K ha^{-1} (data not shown), roughly the same as the growing season average for all fields (3.03 kg K ha^{-1}) (Table 5), suggesting that runoff was not directly related to fertilizer application.

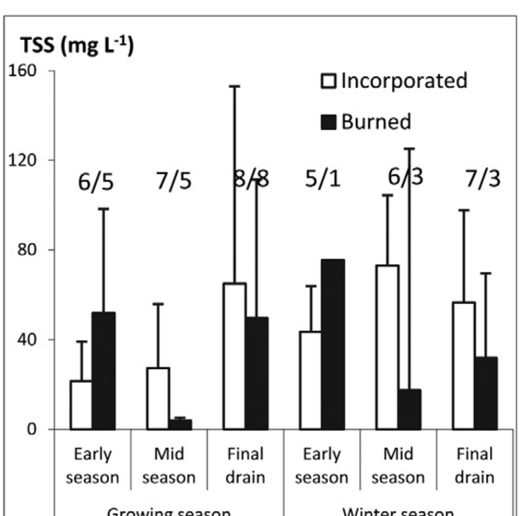
Total Suspended Solids

Concentrations of TSS in irrigation water (Table 3) varied between locations and seasons, which may reflect the different irrigation sources and the different water management strategies used by irrigation districts. For example, some districts recycle runoff water and pump it back into the irrigation supply canals, which will likely increase the TSS concentrations of the irrigation water. Total suspended solid concentrations were similar between the growing and winter seasons (average, 32 mg L^{-1}) (Table 5). However, TSS concentrations were higher during the winter in the fields where straw was incorporated (46 mg L^{-1}) compared with where it was burned (19 mg L^{-1}). The higher winter TSS concentrations where straw was incorporated (Table 5) is likely the result of tillage to incorporate the residue; in contrast, there is usually no tillage in fields where residues are burned. Concentrations of TSS did not vary during the growing and winter seasons (Fig. 3). There was no difference in TSS fluxes between seasons or straw management practices, with average fluxes being 147 kg ha^{-1} (Table 5).

The average TSS concentrations in the runoff water from rice fields reported here are low compared with other studies that have examined rice systems (Poudel et al., 2013; Sanchez et al., 2012; Feagley et al., 1992). Furthermore, these values are similar to TSS values often found in the Sacramento River (Hestir et al., 2013), where much of the runoff water flows. These data, along with the fact that the average TSS concentrations in inflow (Table 3) and runoff water Table 5) were relatively similar, suggest that rice systems are not a major source of the TSS found in the river.

Fields as Sources or Sinks for Nutrients

When net loads were evaluated (input flux – runoff flux), during the growing season rice fields were not a significant source or sink of NO_3–N and NH_4–N (Fig. 4). Net growing season loads averaged -0.03 ± 0.42 kg ha^{-1} and 0.44 ± 0.58 kg ha^{-1} for NH_4–N and NO_3–N, respectively. During the winter fallow, fields were not a source or sink of NO_3–N but were a source of NH_4–N. However, NH_4–N net loads were generally low (0 to -1 kg N ha^{-1}) but increased with increasing water flux (Fig. 4). Given the amount of fertilizer N applied to rice (90–185 kg



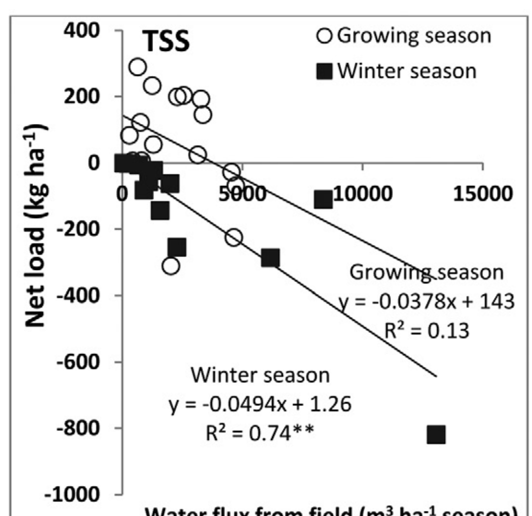


Fig. 3. Average (over sites and years) total suspended solids (TSS) during the growing and winter seasons for fields in which the residue was either burned or incorporated during the winter. The relationship between net TSS load (TSS input minus runoff loads) and water flux from rice fields is shown on the right. A negative load value indicates that the field was a source of TSS. *P < 0.05; **P < 0.01.

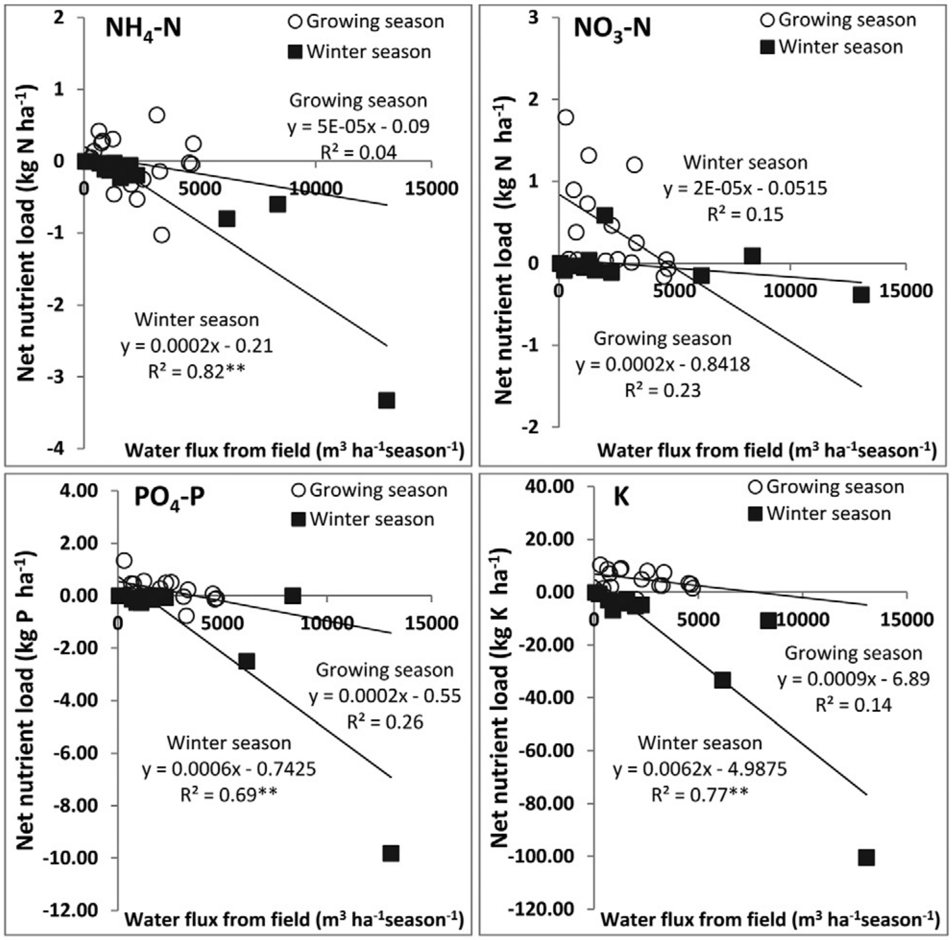


Fig. 4. Relationship of net nutrient load (nutrient input minus runoff fluxes) and water flux from rice fields. A negative value indicates that the field was a source of that nutrient. ****P* **< 0.05; *****P*** **< 0.01.**

N ha^{-1} in this study), <1% of the N applied as fertilizer left the field annually in surface water, unless there were high water fluxes. However, even in the case of Field 1, which had very high winter water fluxes, the net annual (2006 growing and 2006–2007 winter seasons) mineral N load was −4.1 kg N ha^{-1}, which was 4.4% of the fertilizer N applied.

Net P loads averaged 0.21 ± 0.46 kg P ha^{-1} during the growing season, indicating that rice fields were not a major source or sink of P. However, during the winter fallow, fields could be a source of P, especially at high flow rates. For example, the net load in Field 1 (very high flow rates during the 2006 winter) was −9.8 kg P ha^{-1} (Fig. 4), representing 35% of the amount of fertilizer applied to this field (Table 2).

During the growing season the fields were a sink for K, with fields retaining 4.9 ± 3.7 kg K ha^{-1} (Fig. 4), most likely attributable to plant uptake. Rice plants take up significant amounts of K, and at harvest the rice straw and grain contain about 1.39 and 0.27% K, respectively (Dobermann and Fairhurst, 2000). Assuming a harvest index of 0.5 and the average yield reported in these studies of 10.7 Mg ha^{-1}, the amount of K in the crop at harvest was 178 kg K ha^{-1}. Roughly 80% of this K (149 kg K ha^{-1}) is in the straw, explaining why rice fields can be a source of K during the winter fallow period. This K is easily washed out of the straw during the winter (Bakker and Jenkins, 2003) and is susceptible to runoff after flooding or rainfall. During the winter, fields were a source of K, averaging a net load of −15 kg K ha^{-1}. Losses were positively correlated to water flux (Fig. 4), and at high water flux rates (13,060 m^3 ha^{-1} season^{-1}) net K loads were −100 kg ha^{-1} (more than double the fertilizer applied annually). Therefore, minimizing winter water fluxes is an important strategy to reduce K losses.

During the growing season, rice fields were sinks for TSS (net load, 58 kg ha^{-1}); however, rice fields were sources of TSS in the winter (net load, −154 kg ha^{-1}) (Fig. 3). Thus, on an annual basis, rice fields are a source of about 100 kg TSS ha^{-1}. Nutrients can leave fields in soluble forms or attached to suspended solids, such as clay particles (Sharpley et al., 2001). We did not determine the amount of extractable or total nutrients in the TSS; however, we can estimate the importance of TSS losses to overall nutrient budgets. Linquist and Ruark (2011) found that soils from conventional California rice fields contained, on average, 377 mg kg^{-1} total P. Assuming the TSS is composed of all soil (which it is not), 100 kg ha^{-1} of soil would represent a loss of 0.037 kg P ha^{-1}. In the same study, Linquist and Ruark (2011) found that the soil organic carbon content averaged 1.3%. Making similar assumptions, this suggests an annual loss of 1.3 kg C yr^{-1} and roughly 0.1 kg total N yr^{-1} (assuming a C:N ratio of 12:1). Therefore, nutrient losses through TSS runoff is minor and has little significant effect on overall field nutrient budgets. Similar findings were reported by Tian et al. (2007), who found that dissolved N, rather than particulate N, was the main form of N runoff in the rice systems they investigated in China.

Summary and Conclusions

This study evaluated 10 rice fields over a 2-yr period, which varied in terms of residue and water management. In general, N, P, and TSS concentrations in runoff waters, fluxes, and loads were small and not likely to have a large effect on field nutrient balances. From a water quality perspective, runoff water P concentrations were the highest in the winter, particularly from burned fields. In contrast, rice fields behaved as a sink for K during the growing season and as a source for K during the winter. Fields were sources for most nutrients and TSS during the winter when water fluxes were high. These data suggest that one practice to control runoff nutrient losses is to reduce outflow water flux to the extent possible. During the growing season, water is often allowed to flow through the field to help maintain flood levels and to reduce salinity build-up in flood water (Scardaci et al., 2002). During the winter, fields are flooded to aid in straw decomposition (Linquist et al., 2006), but often water is allowed to flow through rice fields for waterfowl.

Another strategy to reduce nutrient loss in outflow water is to avoid applying nutrients into floodwater at the beginning of the growing season or at midseason. In California, most fertilizers are applied before flooding the field for planting. Most of the N is injected about 5 to 10 cm below the soil surface, where it is protected from the effects of surface water flow, and relatively little fertilizer is applied midseason (in this study midseason fertilizer applications were not made). When midseason applications are made, other studies suggest that water flows should be stopped for a period of time after application to avoid nutrient losses and potential off-site contamination.

Acknowledgments

Funding for this project was provided by the California State Water Resources Control Board's Nonpoint Source Pollution Control Grant Program. The authors thank Robert Rousseau, Ligia Bacchereti Azevedo, Luis Felipe Tiene da Silva, Steve Bickley, and Karen McCalister for help with laboratory analysis, sample collection, and field maintenance.

References

American Public Health Association. 1999. Standard methods for the examination of water and wastewater. APHA, Washington, DC.

American Public Health Association. 1998. Standard methods for examination of water and wastewater. 20th ed. APHA, Washington, DC.

AOAC. 1997. Method 972.43. Official methods of analysis of AOAC International. 16th ed. AOAC International, Arlington, VA.

Bakker, R.R., and B.M. Jenkins. 2003. Feasibility of collecting naturally leached rice straw for thermal conversion. Biomass Bioenergy 25:597–614. doi:10.1016/S0961-9534(03)00053-9

Bouman, B.A.M., A.R. Castaneda, and S.I. Bhuiyan. 2002. Nitrate and pesticide contamination of groundwater under rice–based cropping systems: Past and current evidence from the Philippines. Agric. Ecosyst. Environ. 92:185–199. doi:10.1016/S0167-8809(01)00297-3

Buckley, C., and P. Carney. 2013. The potential to reduce the risk of diffuse pollution form agriculture while improving economic performance at farm level. Environ. Sci. Policy 25:118–126. doi:10.1016/j.envsci.2012.10.002

Buresh, R.J., K.R. Reddy, and C. van Kessel. 2008. Nitrogen transformations in submerged soils. In: J.S. Schepers and W.R. Raun, editors, Nitrogen in agricultural systems. Agron. Monogr. 49. ASA, Madison, WI. p. 401–436.

Cassman, K.G., A. Dobermann, D.T. Walters, and H. Yang. 2003. Meeting cereal demand while protecting natural resources and improving environmental quality. Annu. Rev. Environ. Resour. 28:315–358. doi:10.1146/annurev.energy.28.040202.122858

Central Valley Joint Venture. 2006. Central Valley Joint Venture implementation plan: Conserving bird habitat. U.S. Fish and Wildlife Service, Sacramento, CA.

CRC. 2013. California Rice Commission. http://www.calrice.org/Environment/Air+Quality/Burning+Phase+Down+Law.htm (accessed 21 Nov. 2013).

Doane, T.A., and W.R. Horwath. 2003. Spectrophotometric determination of nitrate with a single reagent. Anal. Lett. 36:2713–2722. doi:10.1081/AL-120024647

Dobermann, A., and T. Fairhurst. 2000. Rice: Nutrient disorders and nutrient management. International Rice Research Institute, Los Banos, Philippines.

Feagley, S.E., G.C. Sigua, R.L. Bengtson, P.K. Bollich, and S.D. Linscombe. 1992. Effects of different management practices on surface water quality from rice fields in south Louisiana. J. Plant Nutr. 15:1305–1321. doi:10.1080/01904169209364397

Gilmer, D.S., M.R. Miller, R.D. Bauer, and J.L. LeDonne. 1982. California's Central Valley wintering waterfowl: Concerns and challenges. In: K. Sabol, editor, Transactions of the forty-seventh North American Wildlife and Natural Resources Conference. US Fish and Wildlife Service, Washington, DC. p. 441–452.

Godfray, H.C.J., J. Pretty, S.M. Thomas, E.J. Warham, and J.R. Beddington. 2011. Linking policy on climate and food. Science 331:1013–1014. doi:10.1126/science.1202899

Hart, M.R., B.F. Quin, and M.L. Nguyen. 2004. Phosphorus runoff from agricultural land and direct fertilizer effects: A review. J. Environ. Qual. 33:1954–1972. doi:10.2134/jeq2004.1954

Hestir, E.L., D.H. Schoellhamer, T. Morgan-King, and S.L. Ustin. 2013. A step decrease in sediment concentration in a highly modified tidal river delta following the 1983 El Nino floods. Mar. Geol. 345:304–313. doi:10.1016/j.margeo.2013.05.008

Hill, J.E., J.F. Williams, R.G. Mutters, and C.A. Greer. 2006. The California rice cropping system: Agronomic and natural resource issues for long-term sustainability. Paddy Water Environ. 4:13–19. doi:10.1007/s10333-005-0026-2

Hogue, B.A., and P.W. Inglett. 2012. Nutrient release from combustion residues of two contrasting herbaceous vegetation types. Sci. Total Environ. 431:9–19. doi:10.1016/j.scitotenv.2012.04.074

Kalra, Y.P. 1995. Determination of pH of soils by different methods: Collaborative study. J. AOAC Int. 78:310–324.

Kang, M.S., S.W. Park, J.J. Lee, and K.H. Yoo. 2006. Applying SWAT for TMDL programs to a small watershed containing rice paddy fields. Agr. Water Manage. 79:72–92. doi:10.1016/j.agwat.2005.02.015

Kitchell, J.F., D.E. Schindler, B.R. Herwig, D.M. Post, M.H. Olson, and M. Oldham. 1999. Nutrient cycling at the landscape scale: The role of diel foraging migrations by geese at the Bosque del Apache National Wildlife Refuge, New Mexico. Limnol. Oceanogr. 44:828–836. doi:10.4319/lo.1999.44.3_part_2.0828

Krupa, M., K.W. Tate, C. van Kessel, N. Sarwar, and B.A. Linquist. 2011. Water quality in rice-growing watersheds in a Mediterranean climate. Agric. Ecosyst. Environ. 144:290–301. doi:10.1016/j.agee.2011.09.004

Liang, X.Q., T. Harter, C. van Kessel, and B.A. Linquist. 2014. Nitrate leaching in Californian rice fields: A field and regional scale assessment. J. Environ. Qual. 43:881–894. doi:10.2134/jeq2013.10.0402

Linquist, B.A., S.M. Brouder, and J.E. Hill. 2006. Winter straw and water management effects on soil nitrogen dynamics in California rice systems. Agron. J. 98:1050–1059. doi:10.2134/agronj2005.0350

Linquist, B.A., J.E. Hill, R.G. Mutters, C.A. Greer, C. Hartley, M.D. Ruark, and C. van Kessel. 2009. Assessing the necessity of surface applied pre-plant nitrogen fertilizer in rice systems. Agron. J. 101:906–915. doi:10.2134/agronj2008.0230x

Linquist, B.A., M.D. Ruark, and J.E. Hill. 2011. Soil order and management practices control soil phosphorus fractions in managed wetland ecosystems. Nutr. Cycling Agroecosyst. 90:51–62. doi:10.1007/s10705-010-9411-3

Linquist, B.A., and M.D. Ruark. 2011. Re-evaluating diagnostic phosphorus tests for rice systems based on soil phosphorus fractions and field level budgets. Agron. J. 103:501–508. doi:10.2134/agronj2010.0365

Lundy, M.E., D.F. Spencer, C. van Kessel, J.E. Hill, and B.A. Linquist. 2012. Managing phosphorus fertilizer to reduce algae, maintain water quality, and sustain yields in water-seeded rice. Field Crops Res. 131:81–87. doi:10.1016/j.fcr.2012.03.005

Matson, P.A., W.J. Parton, A.G. Power, and M.J. Swift. 1997. Agricultural intensification and ecosystem properties. Science 277:504–509. doi:10.1126/science.277.5325.504

McDowell, R.W., A.N. Sharpley, L.M. Condron, P.M. Haygarth, and P.C. Brookes. 2001. Processes controlling soil phosphorus release to runoff and implications for agricultural management. Nutr. Cycling Agroecosyst. 59:269–284. doi:10.1023/A:1014419206761

Murphy, J., and J.P. Riley. 1962. A modified single solution method for determination of phosphate in natural waters. Anal. Chim. Acta 27:31–36. doi:10.1016/S0003-2670(00)88444-5

Nelson, D.W., and L.E. Sommers. 1982. Total carbon, organic carbon and organic matter. In: A.L. Page, editor, Methods of soil analysis. Part 2. Chemical and microbiological properties. Agron. Monogr. 9. ASA and SSSA, Madison, WI. p. 539–579.

Olsen, S.R., and L.E. Sommers. 1982. Phosphorus. In: A.L. Page, editor, Methods of soil analysis. Part 2. Chemical and microbiological properties. Agron. Mongr. 9. 2nd ed. ASA and SSSA, Madison, WI. p. 403–430.

Olson, M.H., M.M. Hage, M.D. Binkley, and J.R. Binder. 2005. Impact of migratory snow geese on nitrogen and phosphorus dynamics in a freshwater reservoir. Freshwater Biol. 50:882–890. doi:10.1111/j.1365-2427.2005.01367.x

Paul, J., and M.S. Negi. 2008. Effect of burning of rice and wheat straw on plant nutrients losses. Crop Res. 36:382–383.

Poudel, D.D., T. Lee, R. Srinivasan, K. Abbaspour, and C.Y. Young. 2013. Assessment of seasonal and spatial variation of surface water quality, identification of factors associated with water quality variability, and the modeling of critical nonpoint source pollution areas in an agricultural watershed. J. Soil Water Conserv. 68:155–171. doi:10.2489/jswc.68.3.155

Rao, A.N., D.E. Johnson, B. Sivaprasad, J.K. Ladha, and A.M. Mortimer. 2007. Weed management in direct-seeded rice. Adv. Agron. 93:153–255. doi:10.1016/S0065-2113(06)93004-1

Rible, J.M., and J. Quick. 1960. Method S-19.0. In: Water soil plant tissue: Tentative methods of analysis for diagnostic purposes. University of California Agricultural Experiment Service, Davis, CA.

Ruark, M.D., B.A. Linquist, J. Six, C. van Kessel, C.A. Greer, R.G. Mutters, and J.E. Hill. 2010. Seasonal losses of dissolved organic carbon and total dissolved solids from rice production systems in northern California. J. Environ. Qual. 39:304–313. doi:10.2134/jeq2009.0066

Sanchez, P.B., D.P. Oliver, H.C. Castillo, and R.S. Kookana. 2012. Nutrient and sediment concentrations in the Pagsanjan-Lumban catchment of Laguna de Bay, Philippines. Agric. Water Manage. 106:17–26. doi:10.1016/j.agwat.2011.07.011

SAS Institute. 2010. SAS/STAT 9.22 user's guide. SAS Inst., Cary, NC.

Scardaci, S.C., M.C. Shannon, S.R. Grattan, A.U. Eke, S.R. Roberts, A. Goldman-Smith, and J.E. Hill. 2002. Water management practices can affect salinity in rice fields. Calif. Agric. 56:184–188. doi:10.3733/ca.v056n06p184

Sheldrick, B.H., and C. Wang. 1993. Particle-size distribution. In: M.R. Carter, editor, Soil sampling and methods of analysis. Canadian Society of Soil Science, Lewis Publishers, Ann Arbor, MI. p. 499–511.

Sharpley, A.N., R.W. McDowell, and P.J.A. Kleinman. 2001. Phosphorus loss from land to water: Integrating agricultural and environmental management. Plant Soil 237:287–307. doi:10.1023/A:1013335814593

Simmonds, M.B., R.E. Plant, J.M. Peña-Barragán, C. van Kessel, J. Hill, and B.A. Linquist. 2013. Underlying causes of yield spatial variability and potential for precision management in rice systems. Precis. Agric. 14:512–540. doi:10.1007/s11119-013-9313-x

Sparks, D.L. 1996. Methods of soil analysis. SSSA, ASA, Madison, WI.

Spencer, D.F., and B.A. Linquist. 2014. Reducing rice field algae and cyanobacteria abundance by altering phosphorus fertilizer applications. Paddy Water Environ. 12:147–154. doi:10.1007/s10333-013-0370-6

Tian, Y.H., B. Yin, L.Z. Yang, S.X. Yin, and Z.L. Zhu. 2007. Nitrogen runoff and leaching losses during rice–wheat rotations in Taihu Lake Region, China. Pedosphere 17:445–456. doi:10.1016/S1002-0160(07)60054-X

Tilman, D. 1999. Global environmental impacts of agricultural expansion: The need for sustainable and efficient practices. Proc. Natl. Acad. Sci. USA 96:5995–6000. doi:10.1073/pnas.96.11.5995

USDA. 2013. Fertilizer use and price. U.S. Department of Agriculture, Economic Research Service. http://www.ers.usda.gov/data-products/fertilizer-use-and-price.aspx#26727 (accessed 21 Nov. 2013).

USEPA. 2001. Method 200.7. Trace elements in water, solids, and biosolids by inductively coupled plasma-atomic emission spectrometry. USEPA, Washington, DC.

Wisconsin Department of Natural Resources. 2010. Wisconsin's phosphorus water quality standards. Bureau of Watershed Management, Madison, WI.

Yoon, K.S., J.K. Choi, J.G. Son, and J.Y. Cho. 2006. Concentration profile of nitrogen and phosphorus in leachate of a paddy plot during rice cultivation period in southern Korea. Commun. Soil Sci. Plant Anal. 37:1957–1972. doi:10.1080/00103620600767306

Zhang, Z.H., Y.M. Zhu, P.Y. Guo, and G.S. Liu. 2004. Potential loss of phosphorus from a rice field in Taihu Lake basin. J. Environ. Qual. 33:1403–1412. doi:10.2134/jeq2004.1403

Zhao, X., Y. Zhou, J. Min, S.Q. Wang, W.M. Shi, and G.X. Xing. 2012. Nitrogen runoff dominates water nitrogen pollution from rice–wheat rotation in the Taihu Lake region of China. Agric. Ecosyst. Environ. 156:1–11. doi:10.1016/j.agee.2012.04.024