Nonpoint Source of Nutrients and Herbicides Associated with Sugarcane Production and Its Impact on Louisiana Coastal Water Quality

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A watershed analysis of nonpoint-source pollution associated with sugarcane (*Saccharum officinarum* L.) production was conducted. Runoff water samples following major rainfall events from two representative sugarcane fields (SC1 and SC2) were collected and analyzed. The impact of runoff on two receiving water bodies, St. James canal (SJC) and Bayou Chevreuil (BC) in a drainage basin (Baratarian Basin), was studied. Results show that runoff flow/rainfall ratios at the SC1 were significantly higher ($P < 0.0001$, $n = 14$) than at the SC2, probably mainly due to higher sand content and higher infiltration rate of surface soil at the SC2. In runoff water samples, total suspended solids (TSS) showed a significant correlation with the concentrations of N and P. Sugarcane runoff showed a direct impact on the SJC and BC locations where seasonal variations of pollutant concentrations in the waters followed the patterns of runoff loadings. Swamp forest runoff (SFR) location showed a buffering effect of forested wetlands on water quality with the lowest measured pollutant concentrations. The ratios in total N/total P and in inorganic N/organic N in runoff waters indicated that fertilization in spring greatly contributed to the temporal increase of N loadings, especially in forms of inorganic N. Isotope signature of ^{15}N-nitrate in the water samples verified that the nitrate was derived from fertilizers and was consumed during transportation. Both N and P concentrations in the receiving water bodies were above the eutrophic level. During the study period, herbicide concentrations in the receiving water bodies rarely exceeded the drinking water standards.

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Nonpoint source pollution is the largest remaining type of water pollution in United States that needs to be addressed to restore the designated uses to the impaired water bodies. United States Environmental Protection Agency (USEPA) requires every state to develop a NPS management plan to reduce and control NPS of pollution from various types of land uses that contribute to water quality problems across the country (Clean Water Act, 1972, Section 319).

Agriculture is regarded as one of the major NPS of water pollution in coastal Louisiana. Within Louisiana, approximately 69% and 58% of the river kilometers and lakes assessed, respectively, were impacted by NPS pollution (LDEQ, 2002). The survey indicated that BC (29°54′42′′ N, 90°43′48′′ W), which is located in St. James Parish of the upper Barataria Basin, was not meeting the designated uses for fish and wildlife propagation. The water quality problems were mainly related to low dissolved oxygen (DO) caused by organic enrichment, suspended solids, turbidity, and nutrients. In addition, pesticides in surface water can have a deleterious effect on aquatic organisms or contaminate drinking water supplies. Major source of pollutants impacting the water quality of this watershed was runoff from sugarcane field. Various studies on sugarcane production and water quality in Louisiana have been conducted, but most of them were for plot or field scale rather than watershed. Using ^{15}N stable isotope analysis, Lindau et al. (1997) concluded that the elevated concentrations of N found in sugarcane runoff came from fertilizers applied for the sugarcane production. It was determined that runoff water quality was directly related to the application rate of fertilizers and herbicides in fields (Bengtson et al., 1998). Mechanism of retention and loss of major herbicides used for sugarcane production in this region has been explored (Selim, 2003). All the studies have linked sugarcane runoff to the water quality in regional water bodies as well as in Louisiana's Gulf coast (Southwick et al., 1995, 2002).

Historically, sugarcane, which is grown on alluvial soil on the natural levee of the Mississippi River deltaic plain, has been a vital part of the Louisiana agricultural economy for more than 200 yr. Today Louisiana produces about 16% of the total sugar grown in the United States. More than 80,000 ha of sugarcane are grown in the Barataria/Terrebonne Basin, of which 9700 ha are planted in

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Abbreviations: BC, Bayou Chevreuil; LDEQ, Louisiana Department of Environmental Quality; MCL, maximum contaminant level; NPS, nonpoint sources; SC, sugarcane; SFR, swamp forest runoff; SJC, St. James canal; TSS, total suspended solids.

the studied area (American Sugarcane League, 2000). The majority of sugarcane runoff directly enters Louisiana Gulf coast drainage basins through a series of ditches and canals.

There is a clear link between coastal water quality and land use activities that drain into the coastal drainage basin. To determine sources and predict occurrence of low O_2 and amount of pesticide entry in the water bodies, Louisiana Department of Environmental Quality (LDEQ) needs information on O_2–demanding pollutants (mainly suspended sediments and nutrients) and pesticides entering the water bodies. Measurement of sources from both agriculture and pristine or forested swamps are needed to differentiate the natural background loads from the anthropogenic loads for developing strategy to implement BMPs and for determining total maximum daily loads (TMDL). The specific objective of this 2-yr watershed scale study was to determine the amount of suspended sediments, nutrients, and pesticides loading into the water bodies from sugarcane runoff in the upper portion of Louisiana Barataria Basin, an important coastal estuary. Data from this watershed scale study provide LDEQ information for determining loading rates associated with sugarcane production in the Basin. These data generated can be incorporated into watershed plans, which will guide efforts to improve water quality within this part of the State.

Material and Methods

Sampling Locations

The map of the study area and five sampling locations chosen for this study is shown in Fig. 1, and general descriptions of the locations are summarized in Table 1. Runoff from the sugarcane fields located on the elevated natural levee of the Mississippi River flows along the elevation gradient into adjacent wetland on coastal drainage basin. Water is diverted through a series of drainage ditches and canals into St. James Canal (receiving runoff from an area of approximately 6000 ha = 6×10^7 m^2), which discharges into BC, which in turn discharges into Baratarian Basin, an estuary connected to the Gulf of Mexico.

Two representative sugarcane fields were selected for this study. ISCO automated water samplers (ISCO, Inc., Lincoln, NE) were installed at the edge of the sugarcane fields. Production at the two sugarcane monitoring sites generally used similar practices as related to fertilizer, herbicide application, and residue management. At SC1 the same management practice was applied in both 2005 and 2006 with 135 kg ha^{-1} N fertilizer in April, and 1.40 and 1.12 kg ha^{-1} metribuzin in February and May, respectively. At SC2, N fertilizer was applied at 145 kg ha^{-1} in April 2005, and metribuzin was applied only once in March at 1.40 kg ha^{-1}. No fertilizer and herbicides were applied at SC2 in 2006, because the site was in fallow during the year. Mississippi River alluvial soils are generally high in P and sugarcane commonly shows no response to P addition, thus no P fertilizer was applied at sugarcane field. Weed control for sugarcane production usually requires two herbicide applications, one in early spring and the other before the crop canopy closes (commonly referred as layby treatment in southern Louisiana). Atrazine is sometimes applied following winter harvest, but not at the two sugarcane fields in this 2-yr study period. For SC1, the sugarcane stubble was second year in 2005, and third year in 2006. For SC1, the sugarcane stubble was third year in 2005 following by a fallow in 2006. The sugarcane residues were left on the field without burning after harvest at both sites.

To determine the impact of sugarcane runoff on the water quality of receiving water bodies, grab water samples were collected at the same rainfall event from the following three locations: (i) St. James Canal—south of the discharge of the southernmost field where automated samplers were placed. The purpose of this sampling site was to monitor the area immediately impacted by the sugarcane runoff; (ii) Bayou Chevreuil—near the bridge on LA 20. The purpose of this sample site was to monitor any impact of sugarcane runoff to downstream water bodies and to link the project with a long-term LDEQ water quality monitoring station; (iii) Swamp Forest Runoff—a representative area receiving outflow from a pristine swamp forest. Runoff from this site was used as an index to evaluate background inflow to BC from forested wetlands.

Sampling Procedure

At each sugarcane field, an ISCO water sampler was installed for sample collection at edge-of-field that drains into a major drainage channel and canal. The system is powered by a 12-V battery that can be charged by a solar panel. A culvert was installed in the drain and the equipment mounted on the top of the culvert. A flow meter was used in conjunction with this installation with an area velocity flow meter. The two automated water samplers were maintained by regular field visits at frequency of two or three times per month to ensure their functions over this 2-yr sampling period. The quantity of rainfall and runoff flow volume was obtained using a rain gauge and the flow meter integrated with each automatic water sampler. Hydrographs at the two sugarcane fields were developed to evaluate the relationship between rainfall and runoff volume. According to the hydrographs, each automatic water sampler was programmed individually to be able to collect no <2-L runoff sample for all the analysis following major rainfall events.

Sampling activity was initiated following a major rainfall event. The grab sample collection was parallel to the rainfall events in which water samples were collected from automatic water samplers at the farmers' fields. Composite water samples were collected by the auto samplers after purging the suction lines. For SC1, 0.3-L water sample was taken for every 150 m^3 runoff flow. For SC2, 0.6-L water sample was taken for every 23 m^3 runoff flow. The sampling program automatically deactivated when the sampling jar was full (9.3 L). After collecting no <2-L water sample from each automated water sampler, grab samples were taken from the other three sites: SJC, BC, and SFR. All water samples were immediately stored in ice and transported to laboratory.

Sample Analysis

Each water sample was homogenized by shaking the sampling jars, and then partitioned into three containers with different preservations for different analysis: (i) 0.5-L plastic

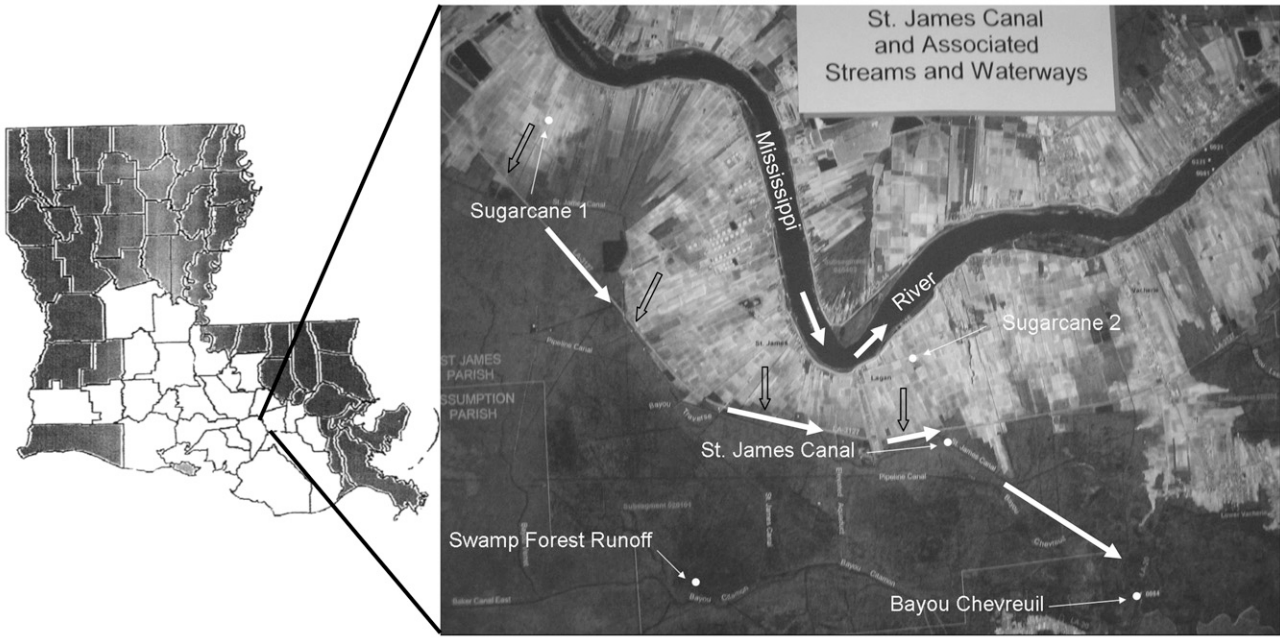

Fig. 1. Map of the study area and sampling locations. Nonshaded areas represent the 24 parishes with sugarcane cultivation. Open black arrows indicate discharge direction of sugarcane runoff to the St. James canal. Solid white arrows indicate flow directions of the Mississippi River and the St. James canal. Selection criteria for each sampling location are described in Table 1.

bottle with no preservative addition for TSS and PO_4^--P analysis; (ii) 1-L plastic bottle with H_2SO_4 addition to pH < 2 for total Kjeldahl nitrogen (TKN), nitrate and nitrite (NO_3^- + NO_2^-), ammonia (NH_4^+), and total P analysis; (iii) 1-L amber glass bottle with HCl addition to pH < 2 for pesticides analysis. All bottles were stored at 4°C ± 2°C before analysis.

Nutrients and TSS analysis were conducted according to the methods described in American Public Health Association (APHA, 1998): TKN (SM 4500), NO_3^- + NO_2^- (SM 4500-NO_3 E), NH_4^+ (SM 4500-NH_3 D), total P and PO_4^--P (SM4500-PE), and TSS (SM 2540 D). Pesticides analysis covered a major spectrum of species using recommended EPA methods (Graves, 1989): atrazine [2-chloro-4-ethylamino-6-isopropylamino-1,3,5-triazine], metribuzin [4-amino-6-(1,1-dimethylethyl)-3-(methylthio)-1,2,4-triazin-5(4H)-one], and terbacil [5-chloro-3-(1,1-dimethylethyl)-6-methyl-2,4(1*H*,3*H*)-pyrimidinedione] (Method 507), pendimethalin [3,4-Dimethyl-2,6-dinitro-N-(1-ethylpropyl)-aniline], trifluralin [a,a,a-trifluoro-2,6-dinitro-N,N-dipropyl-p-toluidine], esfenvalerate [(S)-alpha-cyano-3-phenoxybenzyl(S)-2-(-4-chlorophenyl)-3-methylbutyrate], cyfluthrin [Cyano(4-fluoro-3-phenoxy-phenyl) methyl3-(2,2-dichloroethenyl)-2,2-dimethylcyclopropanecarboxylate],, and lambda-cyhalothrin [(RS)-alpha-cyano-3-phenoxybenzyl 3-(2-chloro-3,3,3-trifluoropropenyl)-2,2,-dimethylcyclopropanecarboxylate] (Method 508). All analysis was subject to appropriate quality control to ensure the data quality.

Calculation and Statistical Analysis

Statistical analysis was conducted using SAS (V8 for Windows, SAS Institute Inc., Cary, NC). Analysis of variance using PROC GLM was conducted to determine the difference of means of sampling events among different sampling locations. Simple linear regression (SLR) using PROC REG was conducted to determine relationships between independent and dependent variables. The significance level was chosen at $\alpha = 0.05$.

Results

Field Runoff following Rainfall Event

Runoff from fields is the portion of precipitation by which NPS pollutants are transported to surface waters. To estimate NPS pollutant loadings from sugarcane production, runoff volumes following major rainfall events need to be determined. During the study period, water samples were taken

Table 1. Sampling locations and selection criteria of each location for the objective of this study.

Sampling site†	Label	Latitude/Longitude	Description
Sugarcane field 1	SC1‡	30°3´1´´ N, 90°54´46´´W	Drainage area 60.7 × 10^3 m^2
Sugarcane field 2	SC2§	29°53´8´´ N, 90°47´53´´ W	Drainage area 40.5 × 10^3 m^2
St. James Canal	SJC	29°57´30´´ N, 90°47´28´´ W	Immediate impact by runoff
Bayou Chevreuil	BC	29°54´42´´ N, 90°43´48´´ W	Runoff impact on lower watershed
Swamp Forest Run-off	SFR	29°55´6´´ N, 90°47´25´´ W	Background reference

† Each sampling location was recorded by Global Positioning System (GPS) coordinates during site visit, and the five sampling locations are labeled in the map (Fig. 1).

‡ Soil in SC1 is classified as silt loam with sand, silt and clay content of 18.3, 56.7, and 25.0%, respectively.

§ Soil in SC2 is classified as sandy loam with sand, silt and clay content of 47.5, 45.0, and 7.5%, respectively.

Table 2. Rainfall and surface runoff flow from the sugarcane fields at each sampling event.

Date	Rainfall		Runoff flow†		Runoff volume		Flow/Rainfall	
	SC1	SC2	SC1	SC2	SC1	SC2	SC1	SC2
	mm				m^3			
17 Mar. 2005	23.6	38.1	16.3	12.1	990.7	489.6	0.7	0.3
1 May 2005	21.8	41.4	15.5	7.6	943.7	308.6	0.7	0.2
31 May 2005	100.3	93.5	65.1	17.6	3948.7	712.9	0.6	0.2
17 July 2005	13.5	14.5	8.2	1.6	496.0	66.0	0.6	0.1
31 Aug. 2005	73.2	68.6	33.6	7.9	2040.4	320.0	0.5	0.1
25 Sept. 2005	113.5	176.3	18.8	20.6	1139.8	832.7	0.2	0.1
Subtotal	345.9	432.4	157.5	67.4	9559.3	2729.8		
24 Jan. 2006	30.2	39.6	19.7	6.7	1194.0	272.6	0.7	0.2
26 Feb. 2006	30.5	21.8	17.0	0.1	1030.5	2.3	0.6	0.0
27 Apr. 2006	64.3	54.1	13.5	0.0	822.1	0.0	0.2	0.0
7 July 2006	23.1	32.5	15.8	0.6	959.7	23.4	0.7	0.0
10 Aug. 2006	73.2	75.0	19.5	6.0	1182.2	244.1	0.3	0.1
13 Sept. 2006	51.1	30.0	28.1	2.1	1702.7	83.3	0.5	0.1
17 Oct. 2006	17.3	17.0	6.3	5.7	385.1	232.8	0.4	0.3
8 Nov. 2006	34.3	29.5	23.9	8.0	1448.0	322.0	0.7	0.3
Subtotal	324.0	299.5	143.7	29.1	8724.3	1180.5		

† Runoff flow (mm) = Runoff volume (m^3) × 1000/Drainage area (m^2). Drainage area for SC1 and SC2 was 60.7 × 103 m^2 and 40.5 × 103 m^2, respectively.

from 14 representative rainfall-runoff events (6 in 2005 and 8 in 2006) at different seasons of the year. Results of rainfall intensities and runoff volumes at these events are summarized in Table 2. At each sugarcane field site, the runoff volumes from the sugarcane fields were positively correlated with the rainfall intensities ($r = 0.61$ for SC1 and $r = 0.77$ for SC2). There was no significant difference ($n = 14$) in rainfall intensity between the two sugarcane fields ($P = 0.76$), but runoff volume from the SC1 was much larger than from the SC2 ($P = 0.0003$).

Measurement of Total Suspended Solids and Phosphorus

Loadings of TSS and P from the SC1 showed much larger variations than from the SC2 (Fig. 2). Average loading rates from the SC1 were higher than from the SC2, but with no statistical significance ($n = 14$) for TSS ($P = 0.07$), total P ($P = 0.09$), and PO_4^--P ($P = 0.07$), respectively. Larger runoff volumes following rainfall events at the SC1 were mainly responsible for the greater loading rates than at the SC2. At the SC2, there were less loadings of TSS ($P = 0.22$), total P ($P = 0.05$), and PO_4^--P ($P = 0.07$) in the 2006 fallow season than in 2005.

Concentrations of TSS and P in waters at the SJC and BC locations generally followed the variations of TSS and P loadings from the sugarcane fields (Fig. 2), indicating a direct impact of sugarcane runoff on water quality in this region. There was no significant difference ($n = 14$) in TSS ($P = 0.15$) and P ($P = 0.11$ for total P, $P = 0.17$ for PO_4^--P) concentrations between the SJC and BC locations. The SFR location showed less impact by the sugarcane runoff, providing good background information for this study. The concentrations of TSS and P at the SFR location were significantly lower ($P < 0.05$, $n = 14$) than at the SJC and BC locations.

Measurement of Nitrogen

Similar results were found for the N measurement (Fig. 3). Average loading rates from the SC1 were higher than from the SC2, but with no statistical significance ($n = 14$) for TKN ($P = 0.06$), $NO_3^- + NO_2^-$-N ($P = 0.20$) and NH_4^+-N ($P = 0.27$), respectively. Greater N loadings from the SC1 than from the SC2 were mainly due to larger runoff volume following rainfall events at the SC1. There were almost no N loadings from the SC2 during the 2006 fallow season due to no fertilization of the field. In general, the variations of N concentration at the SJC and BC locations followed the patterns of N loadings from the sugarcane runoff. The SFR location showed little impact by the N loadings from the sugarcane runoff, and remained low during the study period. The higher concentrations of N at the SJC and BC locations than at the SFR location were due to seasonal impact by sugarcane runoff. Statistically, however, N concentrations among the three grab locations showed no significant difference ($P = 0.14$ for TKN, $P = 0.22$ for $NO_3^- + NO_2^-$-N, and $P = 0.20$ for NH_4^+-N).

Measurement of Herbicides

Atrazine and metribuzin, which were measured in runoff, are the dominant herbicides used in sugarcane production for this region. All of the other measured pesticides levels were below the detection limit of the instrument, and will not be discussed hereafter.

Atrazine was mainly observed in 2005 runoff measurements, and was likely applied before the growing season(s), especially at SC2 site. It should be pointed out that pesticide application may not parallel or to be near the time when field run-off occurs, which in turn would affect concentration in runoff samples. There was no significant difference ($P = 0.34$, $n = 14$) in the loadings of atrazine from the two sugarcane fields, and in the concentrations at the three grab sampling locations. Metribuzin was observed in all water samples during the 2-yr study period. Significantly higher metribuzin loadings from the SC1 than from the SC2 ($P = 0.03$, $n = 14$) may be a result of the following reasons: (i) larger runoff volume from the SC1, and (ii) no metribuzin application in 2006 fallow season at SC2. The SFR location showed significant lower metribuzin concentrations than at the SJC and BC locations ($P < 0.05$, $n = 14$).

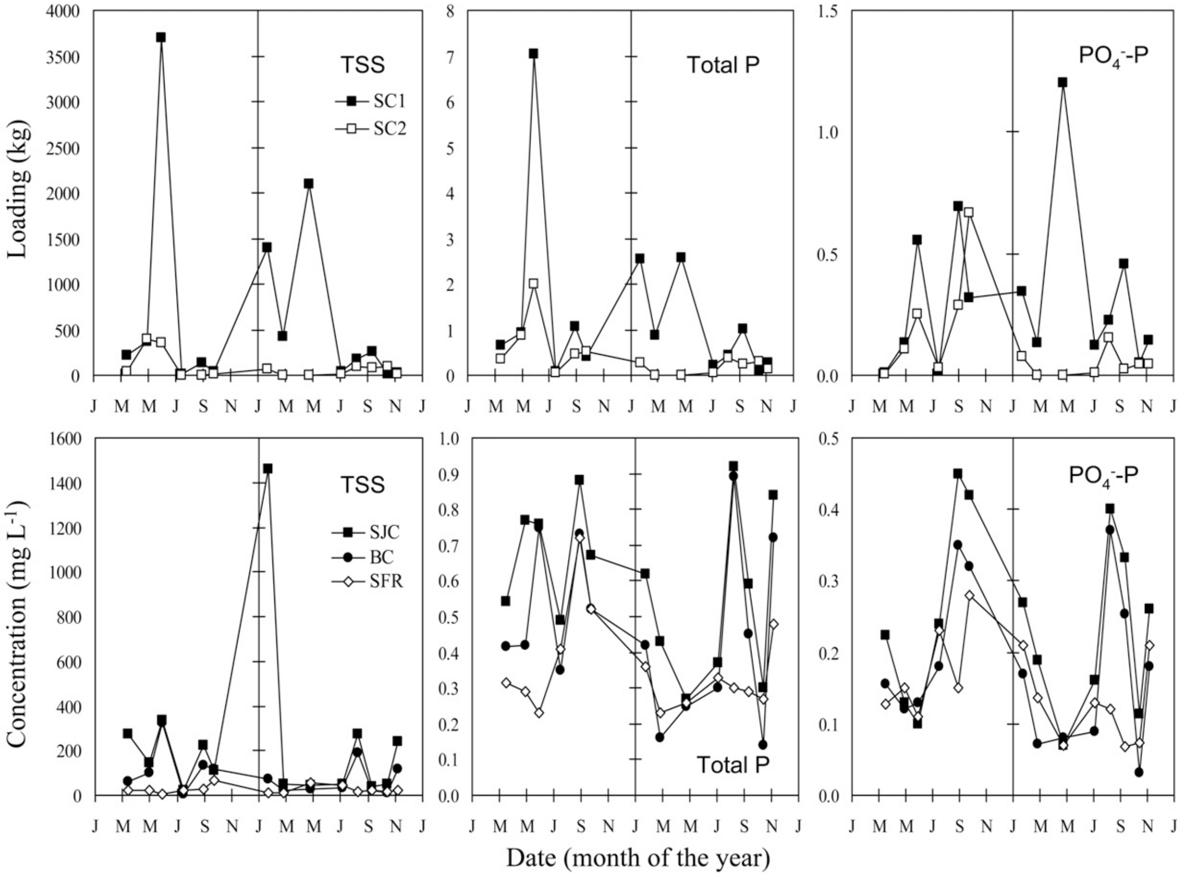

Fig. 2. Loadings of TSS, total P and PO_4^--P from sugarcane runoff following rainfall event and their concentrations at the three grab sampling locations. The results from 2005 are displayed to the left of the *y* axis, and the results from 2006 to the right of the *y* axis. Loading (kg) = Concentration in runoff water (mg L^{-1}) × Runoff volume (m^3)/1000

In contrast to variations in TSS, P and N at the three grab sampling locations, atrazine and metribuzin concentrations at the BC location was occasionally higher than at the SJC location. The concentrations of atrazine and metribuzin at the BC and SJC locations did not follow the variations of loadings from the two sugarcane fields, which suggested impact from other sugarcane fields in the watershed where atrazine and metribuzin may have been applied near or at the time rainfall occurred.

Discussion

Runoff Flow and Precipitation

The factors affecting runoff from agricultural field can be divided into subfactors associated with precipitation and subfactors associated with the field. Precipitation subfactors include intensity, duration, and area of distribution. Field subfactors include size and shape, topography, soil type, and surface cover. During the 2-yr study period, average annual precipitation was 1114 ± 93 mm with no significant difference between the two sugarcane sites ($P = 0.99$). The flow/rainfall ratio at the SC1 was 0.46 and 0.44 for 2005 and 2006 ($P = 0.65$), respectively. The flow/rainfall ratio at the SC2 was 0.16 and 0.10 for 2005 and 2006 ($P = 0.38$), respectively (Table 2). For the same amount of rainfall, the SC1 generated much more runoff flow than the SC2 ($P < 0.0001$, $n = 14$). The major cause for such difference is likely due to higher content of sand in the soil at the SC2 than at the SC1 (Table 1). At the SC2, a large portion of rainfall probably infiltrated, instead of leaving the field as surface runoff. Without transpiration from sugarcane plants in the fallow 2006, the flow/rainfall ratio at the SC2 was surprisingly lower than in 2005. As a preliminary investigation, the Mississippi River stage may be a potential factor responsible for the lower flow/rainfall ratio in 2006 than in 2005 at the SC2. Annual Mississippi River stage was 30% lower in 2006 than in 2005, and most of the lower river stage occurring in the first half of 2006 (data not shown). Consequently, less rainfall water was likely discharged as surface runoff due to lower ground water table, especially at the sandy SC2 location immediately adjacent to the Mississippi River Levee.

Pollutant Loading Rates from the Sugarcane Runoff

When data from all water samples from the two sugarcane fields ($n = 28$) were analyzed, the results indicated that TSS was probably a good indicator of NPS pollution. The amount of TSS showed a strong positive correlation with the concentrations of N and P in the runoff water ($r > 0.8$, $P < 0.01$). However, TSS was weakly correlated with metribuzin concentrations ($r = 0.4$), and not correlated with atrazine concentrations ($r = 0.0005$).

By comparing the results between 2005 and 2006 at SC2, the results clearly showed the impact fertilization on runoff water quality (Table 3). The average loading rate of TSS was about

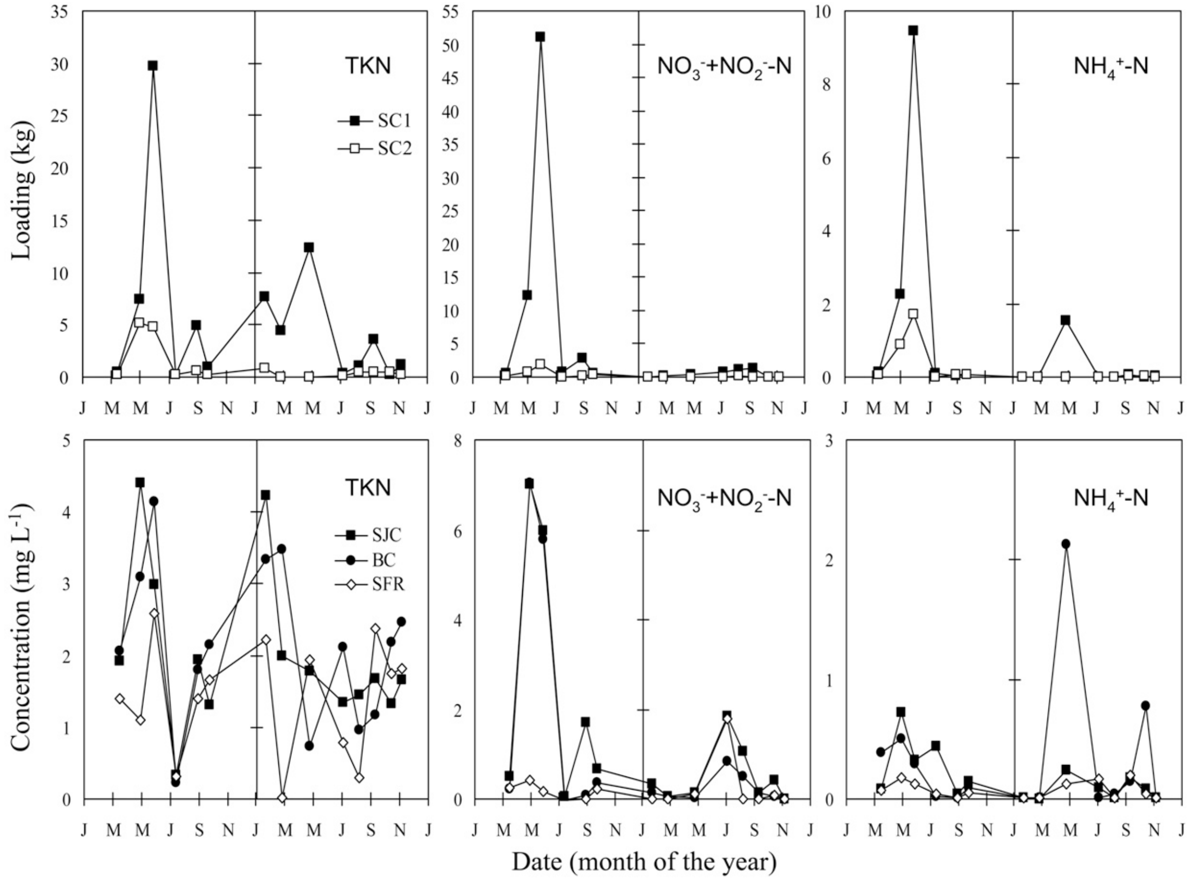

Fig. 3. Loadings of total Kjeldahl nitrogen (TKN), $NO_3^-+NO_2^-$-N and NH_4^+-N from sugarcane runoff following rainfall event and their concentrations at the three grab sampling locations. The results from 2005 are displayed to the left of the *y* axis, and the results from 2006 to the right of the *y* axis. Loading (kg) = Concentration in runoff water (mg L^{-1}) × Runoff volume (m^3)/1000.

three times higher in 2005 than in 2006. Both total P and inorganic P followed the signature of TSS loadings in these 2 yr with average P loading rates in 2005 approximately three times higher than in 2006. However, the average loading rates of N (both organic and inorganic) in 2005 were approximately six times higher than in 2006 at the SC2 location, due to no N fertilization during this fallow year. Timing of N fertilization is critical for its impact on water quality, because most of the N loadings occurred in a short period after fertilization in spring (Fig. 3).

It is not practical to collect and analyze all the runoff water from a field. Therefore, runoff water samples from representative rainfall events must be collected and analyzed to estimate NPS pollutant loading rates. In this study, cumulative rainfall (350 mm) during the 14 sampling events accounted for approximately one-third of the annual precipitation (1114 mm). Annual pollutant loadings from the two sugarcane fields would be three times that summarized in Table 3, if the runoff volume remained the same ratio to rainfall, and average pollutant concentrations in the runoff water remained the same.

Impact of Sugarcane Runoff on Surface Water Quality

The average concentrations of pollutants at the three grab sampling locations are summarized in Table 4. The results showed a general order of pollutant concentrations, SJC > BC > SFR (except the two herbicides in 2005 for unknown reasons). St. James Canal and BC showed clear impacts by the sugarcane runoff, as demonstrated by the elevated pollutant concentrations, especially nitrate + nitrite, in comparison with those in SFR (Table 4). Turbid water was seen at the SJC and BC locations at every sampling event, while SFR location showed water with low turbidity.

It is estimated that about half of the acreage of sugarcane grown in Louisiana receives atrazine and metribuzin as part of management practices (Gianessi and Puffer, 1991). In comparison with atrazine, metribuzin is highly soluble in water with a moderate ability to adsorb to soils with high clay and organic matter content. In sandy soils metribuzin is readily leached (Savage, 1976; Harper, 1988). Thus, metribuzin has a great potential for leaching into and contaminating groundwater. During the study period, the atrazine concentrations in the grab samples exceeded the maximum contaminant level (MCL) for drinking water (3 μg L^{-1}) only once at the BC and SJC locations on 31 May 2005 (Fig. 4, Table 4). The metribuzin concentrations were far below the lifetime health advisory (LHA) level (70 μg L^{-1}) for drinking water (USEPA, 2006).

Organic N was found to be a major N component in the water samples. Nitrate and nitrite, which are highly susceptible to leaching and transport in surface runoff (Sethi et al.,

Table 3. Average loading rates of total suspended solids (TSS), nutrients, and herbicides from the two sugarcane fields.

Analysis	2005 (n = 6) SC1	2005 (n = 6) SC2	2006 (n = 8) SC1	2006 (n = 8) SC2	2005 + 2006 (n = 14) SC1	2005 + 2006 (n = 14) SC2
TSS, kg	744.5 ± 1447.7†	135.2 ± 186.1	554.2 ± 773.6	47.6 ± 42.5	635.8 ± 1067.8	85.2 ± 127.7
Total P, kg	1.7 ± 2.6	0.7 ± 0.7	1.0 ± 1.0	0.2 ± 0.1	1.3 ± 1.8	0.4 ± 0.5
PO_4^--P, kg	0.3 ± 0.3	0.2 ± 0.2	0.3 ± 0.4	0.1 ± 0.1	0.3 ± 0.3	0.1 ± 0.2
Total Kjeldahl N, kg	7.3 ± 11.4	1.9 ± 2.4	3.8 ± 4.3	0.3 ± 0.3	5.3 ± 7.9	1.0 ± 1.7
NO_3^-+NO_2^--N, kg	11.3 ± 19.9	0.6 ± 0.7	0.5 ± 0.6	0.1 ± 0.1	5.1 ± 13.6	0.3 ± 0.5
NH_4^+-N, kg	2.0 ± 3.7	0.5 ± 0.7	0.2 ± 0.5	0.0 ± 0.0	1.0 ± 2.5	0.2 ± 0.5
Atrazine, g	0.4 ± 0.6	10.5 ± 24.9	0.1 ± 0.0	0.0 ± 0.0	0.2 ± 0.4	4.5 ± 16.4
Metribuzin, g	1.3 ± 1.9	0.1 ± 0.2	2.0 ± 3.0	0.1 ± 0.1	1.7 ± 2.6	0.1 ± 0.1

† Data represent mean ± SD. Drainage area for SC1 and SC2 was 60.7 × 103 m^2 and 40.5 × 103 m^2, respectively.

Table 4. Average concentrations of total suspended solids (TSS), nutrients, and herbicides at the three grab sampling locations.

Analysis	2005 (n = 6) SJC†	2005 (n = 6) BC	2005 (n = 6) SFR	2006 (n = 8) SJC	2006 (n = 8) BC	2006 (n = 8) SFR	2005 + 2006 (n = 14) SJC	2005 + 2006 (n = 14) BC	2005 + 2006 (n = 14) SFR
TSS, mg L^{-1}	186.8 ± 113.9‡	123.8 ± 108.1	29.1 ± 20.6	275.6 ± 487.8	61.6 ± 62.0	24.0 ± 16.4	237.5 ± 367.7	88.3 ± 87.1	26.2 ± 17.7
Total P, mg L^{-1}	0.7 ± 0.2	0.5 ± 0.2	0.4 ± 0.2	0.5 ± 0.2	0.4 ± 0.3	0.3 ± 0.1	0.6 ± 0.2	0.5 ± 0.2	0.4 ± 0.1
PO_4^--P, mg L^{-1}	0.3 ± 0.2	0.2 ± 0.1	0.2 ± 0.1	0.2 ± 0.1	0.2 ± 0.1	0.1 ± 0.1	0.2 ± 0.1	0.2 ± 0.1	0.1 ± 0.1
Total Kjeldahl N, mg L^{-1}	2.2 ± 1.4	2.2 ± 1.3	1.4 ± 0.7	1.9 ± 1.0	2.1 ± 1.0	1.4 ± 0.9	2.0 ± 1.2	2.1 ± 1.1	1.4 ± 0.8
NO_3^-+NO_2^--N, mg L^{-1}	2.7 ± 3.0	2.2 ± 3.3	0.2 ± 0.2	0.5 ± 0.6	0.2 ± 0.3	0.3 ± 0.6	1.4 ± 2.2	1.1 ± 2.3	0.2 ± 0.5
NH_4^+-N, mg L^{-1}	0.3 ± 0.3	0.2 ± 0.2	0.1 ± 0.1	0.1 ± 0.1	0.4 ± 0.8	0.1 ± 0.1	0.2 ± 0.2	0.3 ± 0.6	0.1 ± 0.1
Atrazine, μg L^{-1}	1.8 ± 3.1	5.6 ± 12.0	0.4 ± 0.4	0.6 ± 0.9	0.5 ± 0.5	0.4 ± 0.7	1.1 ± 2.1	2.7 ± 7.9	0.4 ± 0.6
Metribuzin, μg L^{-1}	1.0 ± 1.0	1.6 ± 1.8	0.3 ± 0.5	1.3 ± 1.4	0.8 ± 0.8	0.2 ± 0.1	1.2 ± 1.2	1.1 ± 1.3	0.2 ± 0.4

† SJC = St. James canal; BC = Bayou Chevreuil; SFR = swamp forest runoff.

‡ Data represent mean ± SD.

2005), were generally present in higher concentration than ammonium. The ratio of inorganic N/organic N showed large variations, but generally in an order of SC > SJC > BC > SFR (Fig. 5). On 31 May 2005, inorganic N/organic N ratio in the sample collected at SC1 reached up to 10 (Fig. 3 and 5). Organic N in soils and waters can be mineralized into ammonium, and ammonium can be further transformed to nitrate by nitrification process in aerobic conditions. On 1 May 2005, the nitrate concentrations were four times higher in the SC samples and seven times higher in the SFR and BC

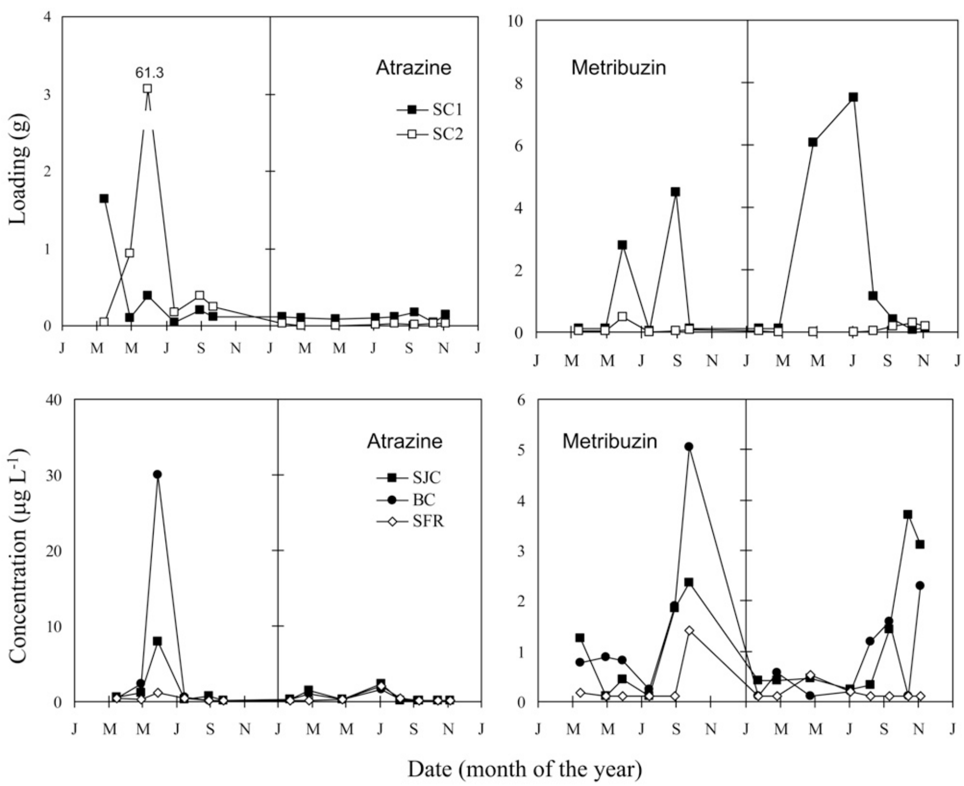

Fig. 4. Loadings of atrazine and metribuzin from sugarcane runoff following rainfall event and their concentrations at the three grab sampling locations. The results from 2005 are displayed to the left of the y axis, and the results from 2006 to the right of the y axis. Loading (g) = Concentration in runoff water (μg L^{-1}) × Runoff volume (m^3)/1000

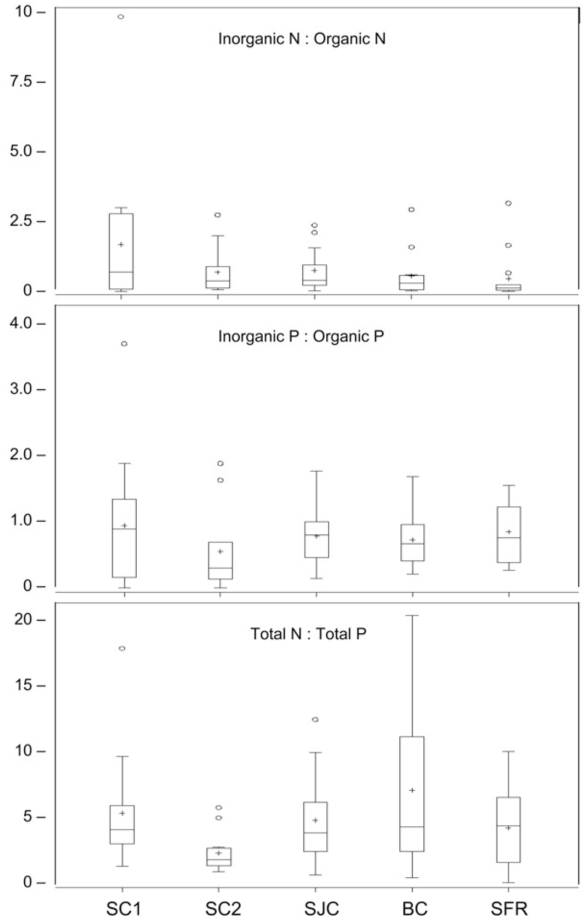

Fig. 5. The ratios of inorganic N to organic N, inorganic P to organic P, and total N to total P in the water samples of the five locations. Data are presented in Box-and-Whisker plots where statistical details are shown, 10th percentile (lower error bar), 25th percentile (bottom edge of the box), means (interior cross), median (interior horizontal line), 75th percentile (upper edge of the box), and 90th percentile (upper error bar).

samples, respectively, than that of ammonium. The results indicate that N fertilization for sugarcane production greatly increased N loadings into surface water bodies, and most of which was in the form of inorganic N that are easily movable and ready for metabolism by water biota. Only at SC1 (Fig. 3), did nitrate concentrations occasionally exceed the MCL (10 mg nitrate L^{-1}) for drinking water (USEPA, 2006).

Isotope signature of ^{15}N-nitrate has been widely used as an indicator of its origin. It has been reported that δ^{15}N-nitrate values are in a range of +10 to +22‰ for municipal and dairy wastewater, +2 to +8‰ for atmospheric deposition, and –3 to +3‰ for fertilizer, respectively (Kreitler et al., 1978; Kreitler and Browning, 1983). The δ^{15}N-nitrate values in the samples of 1 May 2005 were analyzed (Illinois Soil Nitrogen Test, University of Illinois at Urbana-Champaign). The δ^{15}N-nitrate was –2.1‰ (9.1 nitrate mg L^{-1}) and –3.4‰ (0.3 nitrate mg L^{-1}) in the SC1 runoff and SFR sample, respectively. With the nitrate concentration in the waters decreasing from SJC to BC (from 5.5 to 4.0 mg L^{-1}), the δ^{15}N-nitrate value was increased from –1.8‰ to +1.0‰, possibly indicating nitrate consumption mechanisms instead of dilution effect when the water moved from SJC to BC. The results of ^{15}N-nitrate analysis verified that the elevated N concentrations in the water samples were likely due to fertilization in sugarcane fields. However, contribution from mineralization of soil organic N cannot be excluded, because N transformation is an important source of isotope lighter nitrate in soils. Both microbial denitrification activity and aquatic biota metabolism may contribute to the observed decrease in nitrate concentrations and increase in δ^{15}N-nitrate values when the runoff waters traveled from SC1 to SJC and BC (Lindau et al., 1997).

Generally no P fertilization is used in sugarcane production in this region, at least during the study period. The ratios of inorganic P/organic P were in a relatively narrow range, and in average they were about the same in the sugarcane runoff and the three surface water samples (Fig. 5). Organic P represented about 60% of the total P in the water samples. The ratios of total N/total P varied greatly, but the average ratios were quite close among the five sampling locations. Higher total N/total P ratio was found in the spring season each year, following N fertilization in the sugarcane fields.

There is no drinking water standard and health advisory for phosphorus (USEPA, 2006). However, total P levels at the SJC and BC locations (Fig. 2) were found far above the eutrophic status (>0.02 mg L^{-1} for a slow-moving stream) estimated by the U.S. Department of Agriculture (USDA, 1999). Similar results were also found for the total N measurements in this study with eutrophic status >0.3 mg L^{-1} for a slow-moving stream (Fig. 3). Water of low velocity is prevalent in the drainage basins and estuaries of southern Louisiana. The results verified the previous conclusion that the water quality in this part of the Barataria Basin has been impaired (LDEQ, 2002).

Contribution of Runoff from Forested Wetland to Water Quality

The SFR location showed the lowest concentrations of all contaminants determined throughout this study, indicating little contribution of forested wetlands to water quality (Table 4 and Fig. 2, 3, and 4). Total suspended solid was probably a good indicator of contamination because of the strong correlations between TSS and nutrients in the water samples. Vegetation growth in the forested wetlands slows the surface water flow, depositing much of the sediment. This is especially important for removal of P, which is generally associated with soil particles. Elevated levels of nutrients in the runoff water can be used for supporting vegetation metabolism in wetlands. Nitrate is an easily movable contaminant and associated with most of the water quality problems. Higher organic matter content and anaerobic conditions in wetlands are favorable for microbial denitrification to take place by which nitrate is converted to N gases. For all these reasons, there should be a strong effort to maintain or restore wet and vegetated buffers adjacent to streams.

Conclusion and Recommendations

A report of the ecological conditions of U.S. estuaries bordering the Gulf of Mexico estimated that 35% of these water bodies were impaired (USEPA, 1999). Organic enrichment and low DO in these impaired watersheds was attributed to municipal and industrial sources as well as to agriculture production. As demonstrated by this 2-yr watershed analysis study, sugarcane runoff following major rainfall events had an immediate impact or signal (e. g. suspended solids) on water quality receiving streams and water bodies in the northern Barataria Basin. Lower O_2 levels found in the waters of this watershed are largely due to eutrophication and increase of O_2 demand caused by the elevated nutrient levels and suspended solids. Although average total N/total P ratios remained quite close for different sampling locations throughout the year, in fact they were much higher in the spring season each year. Fertilization in spring for sugarcane production greatly increased N loadings into the water bodies, resulting in substantial increases of inorganic N, especially in the form of nitrate. Therefore, water nutrient ratios became more favorable for the aquatic flora to flourish in spring and early summer. Consequently, later decomposition of these aquatic organisms and higher temperature in summer contributed to the concerned low DO in the water bodies.

Agriculture is a major industry in Louisiana and will continue to be important to the state's economy. Sugarcane producers should consider conservation management practices to reduce surface runoff volume and reduction of soil erosion and sediment loss. Best management practices for sugarcane production have been established to address these conservation techniques (Legendre et al., 2000). It is important for sugarcane producers to adopt practices that can maximize N- and P-use efficiency, thereby reduce agricultural contribution to N concentration and potential eutrophic conditions in receiving waters of Louisiana coastal drainage basin. Conservation tillage, compared to conventional tillage, tends to increase infiltration and reduce surface runoff after rainfall (Baker, 1987; Basta et al., 1997; Fawcett et al., 1994). Subsurface drains also increase infiltration at the soil surface and can thereby, like conservation tillage practices, lower runoff losses from a field after rainfall (Southwick et al., 1990). In addition, allowing post-harvest leaf residue to remain in the field rather than burning it shows potential benefits. Leaving the sugarcane residue in the field can enhance sequestration of soluble N within microbial biomass and reduce N transport to receiving waters. Development of new sugarcane varieties with profitable yields under these new conditions should also be considered. Other management practices may include development of edge of field vegetative buffer strips and directing the runoff through settling areas or forested wetland.

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