Determining the nitrate contribution of the Red River to the Atchafalaya River in the northern Gulf of Mexico under changing climate

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Abstract The Mississippi-Atchafalaya River system exports each year over 1.2×10^6 tonnes of nitrate nitrogen into the northern Gulf of Mexico. The excess nutrient load caused by intensive agriculture in the Upper Mississippi River Basin has been attributed to being a major cause of the hypoxic zone in the Gulf. In addition to the land use effect, future climate change may further modify regional hydrology and nutrient fluxes from land to coastal regions. This study was conducted to quantify nitrate mass loading from the Red River, the last major tributary to the Mississippi-Atchafalaya River system, and to assess the effect of future precipitation change in the Red River Basin on its nitrate input into the Atchafalaya River, which is formed by the confluence of the Red River and the Mississippi River via a diversion control structure in Louisiana. Daily river discharge at the diversion structure and the Atchafalaya was gathered for 2007–2009 to estimate the flow of the Red River. Biweekly–monthly nitrate concentrations in the Red River and the Atchafalaya River were measured for the same period to determine the Red River's contribution to the total nitrate mass load in the Atchafalaya River. A precipitation change projection based on the HadCM3 model output for IPCC B1 scenario for the 21st century was taken to discern potential changes in discharge and riverine nitrate load from the Red River Basin. We found that despite making up for nearly one third of the total flow in the Atchafalaya River, the Red River exported a marginal amount of nitrate, namely only about 3% of the total nitrate mass load in the Atchafalaya. With a 6% projected decline in precipitation, nitrate input from the Red River would likely decrease in the future, especially during the drier summer months.

Key words riverine nitrogen; nitrate; climate change; Red River; Mississippi-Atchafalaya River; Gulf of Mexico

INTRODUCTION

Draining 41% of the continental United States, the Mississippi-Atchafalaya River Basin (MARB) discharges over 1 million tonnes of NO_3^- each year into the northern Gulf of Mexico (Goolsby & Battaglin, 2001). This excess nitrogen is mainly a result of intensive agriculture in the upper Mississippi River Basin and has been attributed to be the major cause of the hypoxic dead zone found during early summer off the Louisiana coast (Turner & Rabalais, 1991; Rabalais, 2002). As climate change is predicted for the coming century, further exacerbation of riverine nitrogen loading may occur. Climate change will impact both temperature and precipitation patterns which will affect runoff, evapotranspiration, and nitrogen storage. With global climate change, less productive land will likely be available for agricultural resulting in higher fertilizer use. Both discharge and nutrient concentrations could be affected. However, the magnitude of nitrogen fluxes from the Mississippi-Atchafalaya drainage basin to coastal regions under changing climate is far from certain. The knowledge gap makes it difficult to predict future seasonal hypoxia in the estuaries and continental margins of the northern Gulf of Mexico.

The Red River and 30% of the Mississippi River's discharge forms the Atchafalaya River, which is maintained as a floodway basin for high flow seasons. The basin is considered as a potential area in the lower Mississippi River region for nitrate removal through denitrification. Recent research compared the isotope values of the Atchafalaya River outlets and Mississippi River, finding that the δ^{15}N-nitrate signal was on average 0.7‰ higher on the Mississippi River (BryantMason *et al.*, 2011), which indicates two possibilities: nitrification occurs in the Atchafalaya and/or there is a different source. The Red River flows from Texas and Oklahoma east to Louisiana and is the last major tributary of the MARB prior to reaching the Gulf of Mexico. Although believed not to be a significant player in nitrogen dynamics to the Atchafalaya River, the Red River drains many agriculturally affected tributaries. Fertilizer and nitrified ammonium, both typical of agricultural basins, can result in a lighter δ^{15}N-nitrate, which may explain the finding by BryantMason and colleagues.

The objectives of this study were to determine the relative contribution of the Red River to the Atchafalaya River, both in amount of water and nitrate, and to assess how these relative contributions may be affected by altered precipitation patterns from global climate change.

METHODS

Study area

The 2189 km long Red River flows from northwestern Texas eastward to Oklahoma and Arkansas and south through Louisiana entering the Atchafalaya River just north of the Mississippi River diversion (Fig. 1). The river basin has a total drainage area of 169 890 km^2, predominantly covered by forest (42%), pasture (33%) and agricultural cropland (12%), which is very different to the MARB whose land use is dominated by cropland (58%). The Red River has headwaters in a semi-arid climate; however, as it flows east it encounters a subtropical humid environment. Annual precipitation ranges from about 400 mm in the western part of the Red River Basin to 1500 mm at its confluence in central Louisiana as it flows east.

Fig. 1 Location of the Red River and the Atchafalaya River in the USA.

Data collection

Long-term discharge and nutrient data were obtained from US Army Corps, US Geological Survey, and Louisiana Department of Environmental Quality. Total discharge data from the Old River Control structures were used to represent the fraction of Mississippi River entering the Atchafalaya River. Because the nearest Red River discharge station is Alexandria, Louisiana, it was assumed that the difference between the flow at Simmesport and Old River was the Red River discharge. This was compared to values measured at Alexandria to validate the calculation. Composite water samples were collected biweekly to monthly on the Atchafalaya River at Simmesport from April 2007 to April 2009 and analysed for nitrate and nitrite concentrations.

Data on past precipitation and future precipitation projections for the Red River Basin were derived from outputs of the Hadley climate model using greenhouse gas emission scenario B1. This is a low CO_2 emission scenario with projected CO_2 in the atmosphere of 600 ppm in 2100 (Nakicenovic *et al.*, 2010). Precipitation was used for ecoregion sub-basin 1114 which is the eastern part of the Red River Basin. The percent change in precipitation was used to determine the discharge change. If there was a decrease in precipitation, it was assumed that there was an equivalent reduction in discharge. If precipitation increased, the effective discharge was assumed to increase by half of the precipitation change.

Nitrate mass loading calculation

To estimate nitrate loading using only monthly sampling, a rating curve was modelled to determine the relationship between discharge and nitrate for Red River and Atchafalaya River at Simmesport. The basic power law model:

$$L = aQ^b e^{\varepsilon} \quad (1)$$

which can be log-transformed to:

$$\ln L = \ln a + b \ln Q + \varepsilon \quad (2)$$

where L is daily nitrate load, Q is daily discharge, and ε is an error term assumed to be normally distributed.

The model parameters were determined using the SAS 9.1.3 software package (SAS Institute) and the best fit equations were:

$$\ln L_{Atch} = 1.42664 + 0.853598 \ln Q_{Atch} \quad (3)$$

$$\ln L_{Red} = -0.195634 + 0.887356 \ln Q_{Red} \quad (4)$$

where L_{Atch} and L_{Red} are daily nitrate loads in tonnes at the Atchafalaya and Red rivers, respectively, Q_{Atch} is daily discharge in cubic metres at the Atchafalaya River and Q_{Red} is the daily discharge of the Red River calculated by:

$$Q_{Red} = Q_{Atch} - Q_{Old\ River} \quad (5)$$

Equations (3) and (4) have regression coefficient (R^2) of 0.73 (n = 34, $p < 0.05$) and 0.62 (n = 43, $p < 0.05$), respectively.

RESULTS AND DISCUSSION

Present hydrological conditions and nitrate concentrations

During 2007–2009 discharge in the Atchafalaya River at Simmesport averaged 7132 $m^3\ s^{-1}$, ranging from 2412 $m^3\ s^{-1}$ in October 2007 to 16 586 $m^3\ s^{-1}$ in April 2008 (Fig. 2). This is slightly higher than the long-term average (6500 $m^3\ s^{-1}$) for 1975–2004 calculated by Xu (2010), but within the reported range. A record spring flood in 2008 likely contributed to the higher discharge. During the same period the Red River averaged 2137 $m^3\ s^{-1}$, ranging from 324 $m^3\ s^{-1}$ in November 2007 to 5983 $m^3\ s^{-1}$ in November 2009.

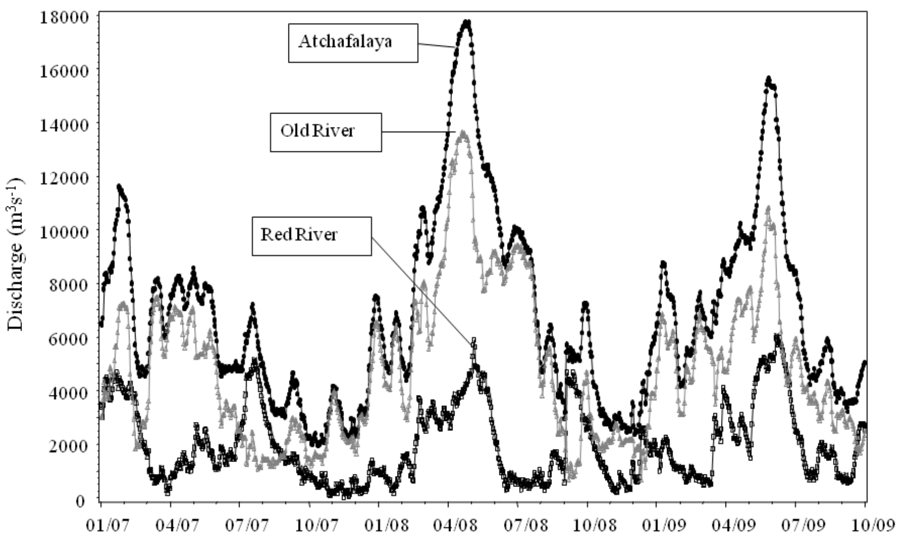

Fig. 2 Discharges of the Red and Old rivers before their confluence that forms the Atchafalaya River.

Nitrate concentration in the Red River was found to be very low, averaging 0.15 mg L^{-1} in a range between 0.03 mg L^{-1} and 0.39 mg L^{-1}. This falls within the lower range of total nitrogen (<0.02 to 20.2 mg L^{-1}) found across the Red River Basin by Longing & Haggard (2010). Atchafalaya River nitrate averaged 1.39 mg L^{-1} ranging from 0.4 to 2.4 mg L^{-1}. The average was lower than that found in the Mississippi River, but higher than the long-term average (0.89 mg L^{-1}) reported by Xu (2006). The large difference in nitrate concentration between these two rivers can be attributed primarily to the difference in land use in the rivers' drainage areas. Also, lower rainfall in the Red River Basin may have produced less surface runoff and subsurface leaching of nitrogen during the study period, when compared with the upper Mississippi River Basin.

Red River contribution to the Atchafalaya River

Despite contributing nearly one third of the Atchafalaya's flow, the Red River exported a marginal amount of nitrate to the Atchafalaya (Table 1). Average monthly nitrate mass loading in the Atchafalaya River was 22 140 tonnes, ranging from 9140 tonnes in October 2007 to 45 920 tonnes in April 2008. The Red River had much lower nitrate loads than the Atchafalaya, averaging 660 tonnes varying from 130 tonnes in November 2007 to 1290 tonnes in May 2008. In a riverine carbon budget (data not shown), we found that organic carbon in the upstream Atchafalaya was higher than the Mississippi River, indicating a source of organic substances from the Red River to the Atchafalaya River.

The Red River fraction of Atchafalaya discharge has a large range: from 7% in July 2008 to 70% in July 2007 (Fig. 3). Interestingly, both extremes were in July. Spring floods in the Atchafalaya can occur early or late in the spring. The Red River makes up a smaller fraction when the Atchafalaya is at high stages. For example, during the 2008 spring flood, the Red River made up about 25% of the Atchafalaya. However, in late summer and early fall, the Red River can make up more than half of the discharge in the Atchafalaya. The fraction does mirror the fluctuations in the Red River (Fig. 2), so it is not only the change in discharge from the Mississippi River that controls the fraction. Because of the low nitrate in the Red River, it acts as a dilution effect to the incoming nitrate rich Mississippi River water.

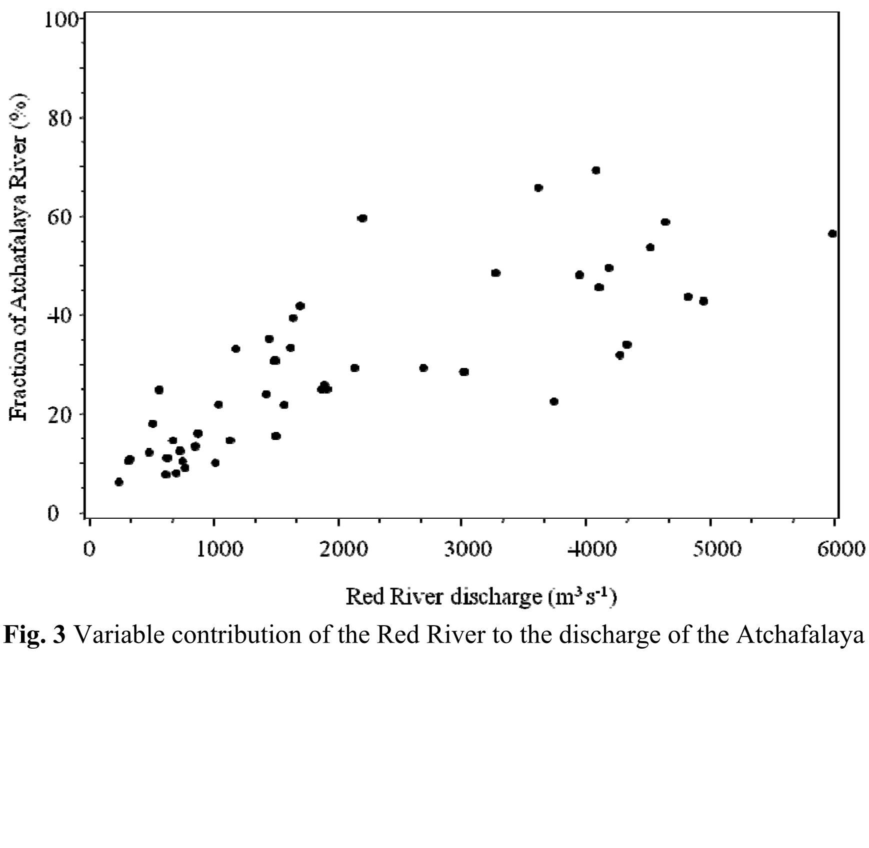

Fig. 3 Variable contribution of the Red River to the discharge of the Atchafalaya River.

Table 1 Past (1950–2010) and projected future precipitation (based on climate change scenario B1) in the eastern Red River Basin, and current (2007–2009) and projected future nitrate loads in the Red River.

Month	Precipitation (mm)				Nitrate (tonnes)			
	1950–2010	2011–2060	Difference	% change	Atchafalaya	Red	Red (future)	% change
January	75	67	–9	–11	24610	850	760	–11
February	82	87	5	6	22850	780	800	3
March	122	122	0	0	26080	770	770	0
April	150	162	12	8	31530	700	730	4
May	129	104	–25	–19	32570	870	720	–17
June	84	71	–14	–16	25900	630	540	–14
July	65	58	–7	–11	22170	560	510	–9
August	62	51	–11	–17	16330	460	390	–15
September	70	74	4	5	14280	530	540	2
October	73	64	–9	–12	15320	560	500	–11
November	89	95	6	7	14380	520	530	2
December	88	82	–6	–6	18850	690	660	–4
Total	1089	1037	–52		264870	7920	7450	
Average	91	86	–4	–5	22073	660	621	–6

Potential climate change effects on nitrate fluxes

Under scenario B1, the eastern Red River Basin would have an overall 5% decrease in rainfall (Table 1). Most of the reduction is during the summer months. Although the lowest rainfall month (August) and the highest rainfall month (April) do not change, the extreme values do with an 11% decrease in August and a 12% increase in April. Accordingly, we reduced monthly discharge from the Red River to estimate its future nitrate load to the Atchafalaya. Based on the calculation, the fraction of the Atchafalaya River from the Red River would drop by as much as 5% and nitrate mass export from the Red River would decrease, but nitrate concentration in the Atchafalaya would increase because the Mississippi River nitrate would be diluted less by the Red River. Although there may be a decreased discharge and nitrate loading to the Atchafalaya, changing precipitation patterns can result in extreme events that cause a large pulse of nitrate flushed from dry soils (Wilby *et al*., 2006). Overall discharge may be decreased, but large pulsing events similar to that seen in April 2008 may become more frequent. Peak nitrate loading in the Red River during the study period occurred in May 2008. This is a very likely possibility because projected precipitation does have wider extremes.

Any change in discharge (positive or negative) due to climate change will affect the nitrate loading of a river. Assuming Atchafalaya River discharge remains constant and any reduction from the Red River results in increased Mississippi River diversion and *vice versa* when Red River discharge increases, the dilution effect of the Red River would impact nitrate that is ultimately released to the Gulf of Mexico by the Atchafalaya. An increased Red River contribution to the Atchafalaya River during extreme weather events can cause one of two possible scenarios for the Atchafalaya River: (1) less nitrate could be present during biologically active time periods because less Mississippi River water could be diverted during these time periods; or (2) discharge could also rise in the Atchafalaya River as the present Mississippi River water estimates could continue to be diverted. The latter may improve nitrate removal through denitrification as more water is introduced to backwater areas. Climate change could cause more extreme seasonality with the lowest nitrate occurring in the summer months (Zweimuller *et al*., 2008). However, during the winter, with additional discharge from rainfall, additional nitrate from nonpoint sources can also decrease the dilution potential of the Red River to the Atchafalaya River. Projections on rivers in the UK show increased nitrates in the winter as a result of increased runoff sources (Whitehead *et al*., 2009). With additional precipitation during February–April, these additional runoff sources may reach the Red River.

SUMMARY

This study quantified the nitrate load from the Red River to the Atchafalaya River for 2007–2009 and assessed the potential effect of future precipitation change in the basin on discharge and nitrate export. The Red River makes up nearly one third of the total flow of the Atchafalaya, and its contribution during low flow conditions in the late summer and early fall can be especially important. Despite the large quantity of flow, nitrate input from the Red River contributes only 3% of the total nitrate mass load in the Atchafalaya. As precipitation patterns in the Red River Basin are projected to decrease, nitrate export from the Red River may decline, especially during the drier summer months. However, these estimates are conservative, because this study used the low emissions scenario (B1), and may have underestimated the effects of climate change on this region. Future studies need to examine loads of other nitrogen species and organic matter from the Red River, as well as the temperature change effect on riverine nitrogen, in order to fully understand the Red River influence on future nutrient transport in the Atchafalaya River.

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