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LETTER

Nitrogen management challenges in major watersheds of South America

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Abstract

Urbanization and land use changes alter the nitrogen (N) cycle, with critical consequences for continental freshwater resources, coastal zones, and human health. Sewage and poor watershed management lead to impoverishment of inland water resources and degradation of coastal zones. Here we review the N contents of rivers of the three most important watersheds in South America: the Amazon, La Plata, and Orinoco basins. To evaluate potential impacts on coastal zones, we also present data on small- and medium-sized Venezuelan watersheds that drain into the Caribbean Sea and are impacted by anthropogenic activities. Median concentrations of total dissolved nitrogen (TDN) were 325 μg L^{-1} and 275 μg L^{-1} in the Amazon and Orinoco basins, respectively, increasing to nearly 850 μg L^{-1} in La Plata Basin rivers and 2000 μg L^{-1} in small northern Venezuelan watersheds. The median TDN yield of Amazon Basin rivers (approximately 4 kg ha^{-1} yr^{-1}) was larger than TDN yields of undisturbed rivers of the La Plata and Orinoco basins; however, TDN yields of polluted rivers were much higher than those of the Amazon and Orinoco rivers. Organic matter loads from natural and anthropogenic sources in rivers of South America strongly influence the N dynamics of this region.

1. Introduction

The remarkably large urbanization rates and the expansion and intensification of agricultural activities in South America have contributed to substantial changes in urban and remote environments (Austin *et al* 2013, Bustamante *et al* 2014). Over the past 60 years, the urban population in South America increased from 40% to nearly 80% and is expected to exceed 85% by the year 2050 (UN-Habitat 2013). Although South America holds only 10% of the world urban population, its disproportionate distribution has allowed the development of megacities with more than 10 million people (São Paulo, Buenos Aires, and Rio de Janeiro) along with associated inherent problems, such as the spread of water-borne diseases and increased pressure on water resources because of the lack of sewage treatment (Austin *et al* 2013).

Currently, 100 million people still lack access to any sanitation, with rural access at just 60%. Additionally, only 20% of wastewater in South America is treated, leading to the pollution of rivers and coastal areas (Ometto *et al* 2000, Daniel *et al* 2002). In tropical and subtropical areas the amount of freshwater stored in reservoirs has increased substantially in the past 50 years, as well as N and phosphorus loading to this system (Nilsson *et al* 2005). Consequently, a key challenge for many South American countries is to further improve water management, including the reduction of N pollution.

Human activities have roughly doubled the global production of reactive N compared to its pre-industrial level, and production is expected to continue increasing (Galloway *et al* 2008). The impacts of changes on the N cycle in South America and the interactions with other altered biogeochemical cycles are still open issues (Martinelli *et al* 2006). Assessing the effects of a changing N cycle in the region is also critical for understanding the state of the continent's considerable freshwater resources (Martinelli *et al* 2010, Roland *et al* 2012), with important linkages between food and water security, ecosystems, and human health.

Currently, the geographic extent and timing of anthropogenic enhancement of N inputs in both terrestrial and aquatic ecosystems of South America are poorly constrained, and the impacts of these changes have not been comprehensively assessed. In this study, we focus on land–water interactions and N loads in the context of urbanization and agricultural expansion/intensification in South America through the comparison of case studies: the large Amazon, La Plata, and Orinoco basins that account for about two-thirds of the region's average annual runoff. Because the total dissolved nitrogen (TDN) load from all small- and medium-sized tropical rivers impacted by anthropogenic sources is equal to or greater than that of the largest tropical rivers in the world (Rasse *et al* 2015), we also review data on small- and medium-sized Venezuelan watersheds that drain into the Caribbean Sea and are impacted by anthropogenic activities (figure 1).

2. The Amazon, La Plata, and Orinoco basins and small- and medium-sized watersheds in northern Venezuela

As the largest river basin the world, the Amazon Basin covers an area of approximately 6.3 million km^2, which comprises about 40% percent of the South American continent and encompasses the countries of Bolivia, Brazil, Colombia, Ecuador, Guyana, Peru, Suriname, and Venezuela. Most of the basin is covered by a tropical rainforest, considered one of the most diverse biomes on Earth. In the Amazon Basin, human population density is very low and concentrated in large cities. The Amazon River headwaters are located in Peru at approximately 5600 meters above sea level, and the river flows about 6500 km before meeting the Atlantic Ocean. Average rainfall is about 2300 mm annually, varying from about 6000 mm in the eastern Andean slopes to 1500 mm in the extreme south.

By 2012 some 750 000 km^2 of forest, or about 20% of the original forest extent of the Brazilian Legal Amazon, had been cleared. Annual deforestation rates in the Brazilian Amazon fell by 77% between 2004 and 2011 but have stabilized since 2009 at 5 000–7 000 km^2 per year (www.obt.inpe.br/prodes/index.php). Deforestation changes the hydrological, geomorphological, and biogeochemical states of streams by decreasing evapotranspiration on the land surface and increasing runoff, river discharge, erosion, and sediment loads from the land surface (Neill *et al* 2011).

The main inputs of N to the Amazon region is biological N fixation (BNF) in natural ecosystems and, more recently, N fertilization from agricultural practices (Filoso *et al* 2006, Martinelli *et al* 2006). In the Brazilian Amazon, forest clearing for pastureland has been the dominant land-use transition for decades. However, Galford *et al* (2010) reported a shift to crop agriculture in recent years, particularly in the southern Amazon region. The most common type of intensification in this region is a shift from single- to double-crop rotation and the associated changes in management, including increased fertilization (Galford *et al* 2010). BNF is approximately 7700 Gg yr^{-1} in the Amazon tropical forest and 1700 Gg yr^{-1} in agricultural lands, mainly due to soybean cultivation. The use of N fertilizers is on the order of 480 Gg yr^{-1} (Martinelli *et al* 2012). The major output N flux is riverine, equal to 3300 Gg yr^{-1}, and yield related to food products (mainly the transport of soybean and beef). Therefore, the riverine output flux is approximately one-third of the total N input (Howarth *et al* 1996).

The La Plata River Basin is the second largest river system in South America (extending over 3.1 million km^2) and the fifth largest in the world. Shared by Argentina, Bolivia, Brazil, Paraguay, and Uruguay, it covers about one-fifth of South America. The La Plata River Basin is at the core of the region's socioeconomic activities, which generate approximately 70% of the per capita gross domestic product of the aforementioned five countries (Coutinho *et al* 2009). The topography of the basin is highly variable, ranging from 4000 m high mountains in northwestern Argentina and southern Bolivia to the almost sea-level southern plains of Argentina and Uruguay. Rainfall similarly varies, from less than 700 mm yr^{-1} in the western Bolivian highlands to more than 1800 mm yr^{-1} along the eastern side of the Brazilian portion of the basin.

The influence of the La Plata River extends along a 1300 km coastal strip (Piola *et al* 2005) through Argentina, Uruguay, and Brazil. The La Plata Basin hosts more than 30 large hydropower reservoirs and water withdrawals for agriculture, human and industrial consumptions, and associated land use changes (Popescu *et al* 2012), which severely impact the natural flow of sediments and nutrients downstream to the Plata Estuary between Argentina and Uruguay.

In terms of freshwater potential, the Paraná River is the most important in the La Plata River basin, with a mean annual flow of about 17 100 m^3 s^{-1} at Corrientes (UNESCO-WWAP 2006), exceeding 20 000 m^3 s^{-1} at the estuarine zone. The share of irrigated land is relatively low, ranging from 2% in Paraguay to 15% in Uruguay. Nevertheless, in all the countries of La Plata Basin, agriculture accounts for most of the overall water consumption: from 62% in Brazil to 96% in Uruguay (FAO 2004). Furthermore, total soybean production in Argentina, Bolivia, Brazil, and Paraguay is expected to rise by about 85% by 2020. It is important to point out that about 10% of the

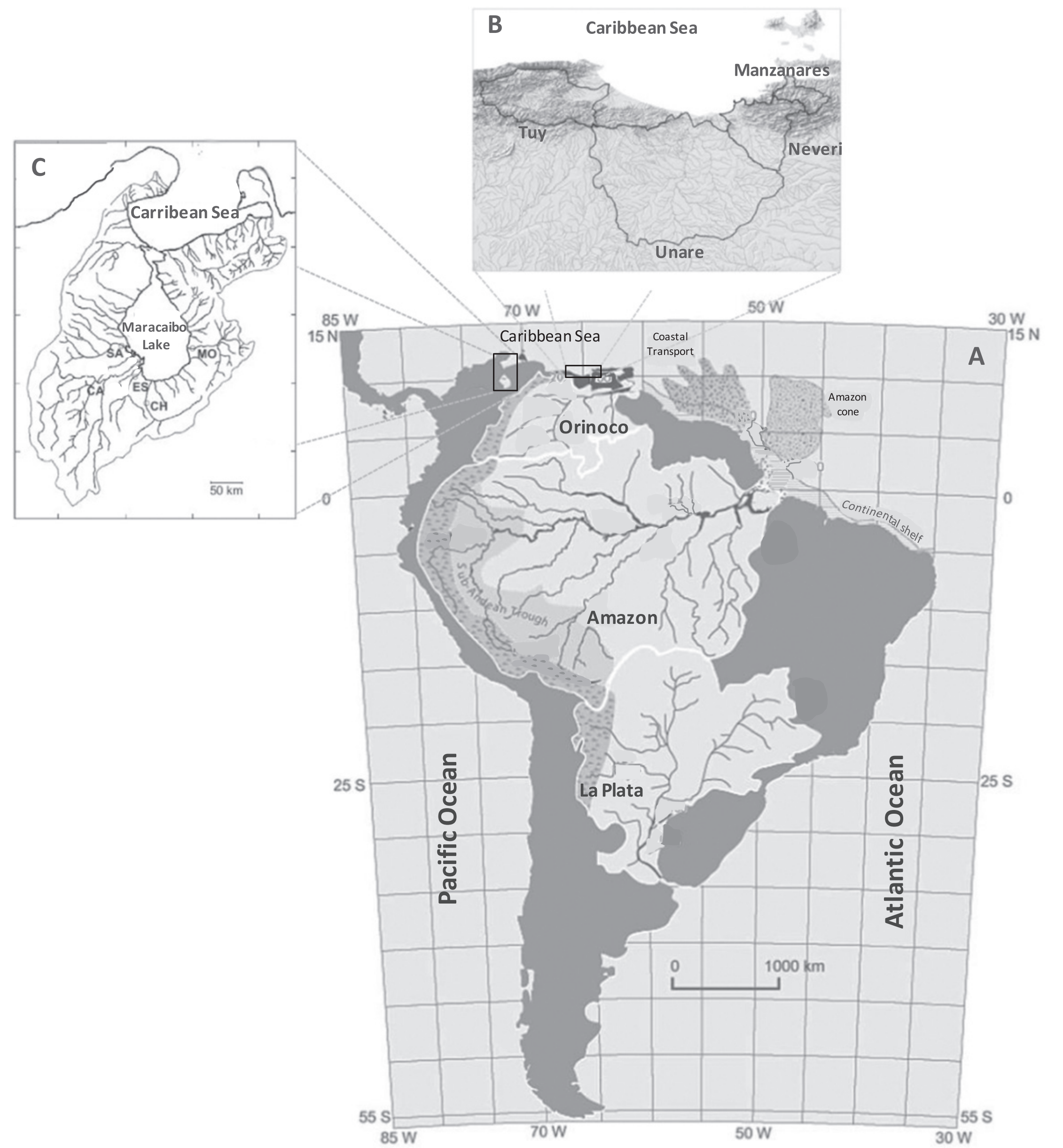

Figure 1. Map showing South America's major river basins and small- and medium-sized rivers of northern Venezuela. (a) The main basins of South America: Orinoco, Amazon, and La Plata. (b) The Tuy, Unare, Neveri, and Manzanares rivers. (c) The Santa Ana (SA), Catatumbo (CA), Escalante (ES), Chama (CH), and Motatan (MO) rivers. Source: modified from Dumme and Kerry Mertes (2007), Rivas *et al* (2005), and Rasse *et al* (2015).

Brazilian cattle are raised in the La Plata Basin (UNESCO-WWAP 2007).

The vast agricultural and grazing area in the Brazilian portion of the La Plata Basin contributes to the alteration of the N cycle in South America. Soybean production plays a very important role in the Brazilian La Plata, since it contributes an annual input of about 1800 Gg, due to BNF, and the export of soybean products accounts for roughly 1000 Gg (Watanabe *et al* 2012). This export of soybean products is greater than the total annual riverine N exports from the rivers of Brazilian Parana, Paraguay, and Uruguay (approximately 500 Gg).

The Orinoco Basin is the largest in Venezuela and the fifth largest river in South America, with an area of 1×10^6 km^2 distributed 70% in Venezuela and 30% in Colombia. It encompasses a wide array of ecosystems, from the Andes and Cordillera de la Costa to the northwest, plains to the southwest and northeast, and the Guyana shield to the south (Warne *et al* 2002). The basin, which drains to the east into the Atlantic Ocean, has a large precipitation range because of its watershed length and various ecosystem types, with an area-weighted mean precipitation of 2270 mm yr^{-1} (Lewis *et al* 1989). The vegetation consists of dry, moist, or very moist premontane or montane forests in the headwaters of the basin, dry tropical forest and savanna vegetation in the lowlands, and an array of savannas and tropical rainforests in the Guyana shield tributary watersheds. The Orinoco has extensive floodplain forests (about 940 km^2) and is considered a largely unperturbed watershed because of the limited industrial and agricultural development along the basin (Lewis *et al* 1999).

In the eastern Llanos are located small- and medium-sized rivers (the Unare, Neverí, Tuy, Manzanares, Catatumbo, Motatan, Escalante, Chama, and Santa Ana) that discharge into the Caribbean Sea. These watersheds, which encompass a variety of land use types, are under enormous pressure, primarily because most of the Venezuelan population is concentrated in the northern part of the country (www.ine.gov.ve/CENSO2011/). In Venezuela, 26% of the savannas are under agricultural management (López–Hernández et al 2005), and in recent years, large forest areas have been cleared to expand the agricultural frontiers (Abarca and Barnabé 2010), with several environmental implications (Marquina *et al* 2013). For example, corn, which represents 65% of the total national cereal production, requires considerable amounts of N fertilizer (80–120 kg N ha^{-1} per cycle), but only 18% to 48% of the N applied is taken up by the crop (Hetiér *et al* 1989, Delgado I 2001, Cabrera–Bisbal 2003, Delgado and Salas 2006, Marquina 2010). In addition, untreated wastewater derived from urban/industrial activities is directly discharged into the watersheds, which has drastically modified N dynamics in these tropical rivers (Rasse *et al* 2015).

3. Nitrogen forms and distribution in rivers of South America

Table 1 summarizes the dissolved N forms in rivers of the three major watersheds in South America and the small- and medium-sized Venezuelan watersheds that drain into the Caribbean Sea. The dissolved inorganic nitrogen (DIN) concentration in the major rivers of the Amazon Basin ranges from approximately 30–200 $\mu g\ L^{-1}$, with a median value of 134 $\mu g\ L^{-1}$. The lowest concentrations were observed in the black-water rivers (Negro and Jutaí), and the highest concentrations were observed in white-water rivers, especially in the Amazon River at Óbidos and in the Juruá and Madeira tributaries (table 1). Nitrate is the main component of DIN in rivers of the Amazon Basin. In the main channel (Manacapuru and Óbidos) and in the major black-water tributaries, nitrate represents more than 90% of the DIN (data not shown). The same is true for the Orinoco River, where the mean discharge concentration of DIN is 115 $\mu g\ L^{-1}$, 70% of which is nitrate (Lewis *et al* 1989). The DIN concentrations in the two small streams of the Amazon were lower than those observed in the major rivers. However, the presence of ammonium is much more common in these small streams than in the major rivers. For instance, in forest streams DIN is composed of 40% nitrate and 60% ammonium on average (Neill *et al* 2001). In pasture streams nitrate accounts for only 15% of the DIN, and the remaining 85% is ammonium (Neil *et al* 2001). DIN concentrations in rivers of the La Plata Basin were higher than in the rivers of the Amazon Basin. The median DIN of these rivers was approximately 680 $\mu g\ L^{-1}$, which is approximately five times higher than in the Amazon Basin (table 1). In particular, very high DIN concentrations were observed in the Atibaia, Jaguari, and Piracicaba rivers (Martinelli *et al* 1999). Similar to La Plata, the polluted small- and medium-sized rivers of Venezuela have DIN concentrations (278–6499 $\mu g\ L^{-1}$) (table 1) that are 2–60 times larger than that found in the Orinoco River. The Tuy River, which belongs to a watershed highly impacted by urban/industrial land use in Venezuela, had the highest DIN concentration, with ammonium as the dominant species (60% of total DIN) (Rasse *et al* 2015).

Dissolved organic N (DON) concentrations in Amazon rivers varied from approximately 140 to 300 $\mu g\ L^{-1}$ (table 1), with a median DON value (176 $\mu g\ L^{-1}$) higher than the median DIN value (approximately 680 $\mu g\ L^{-1}$). In contrast, TDN is quite constant among Amazon rivers, with a median value of 325 $\mu g\ L^{-1}$. The DIN:DON ratios were generally equal to or lower than 1, evidencing the dominance of the organic over inorganic dissolved N forms, especially in black-water rivers (Negro and Jutaí) and white-water tributaries (Içа and Purus) (table 1). Similarly, in the Orinoco River the mean discharge concentration of DON (160 $\mu g\ L^{-1}$) was greater than that of DIN (Lewis *et al* 1989). In general, the DON concentrations of rivers in the La Plata Basin were lower than those of the rivers in the Amazon Basin. Therefore, most DIN:DON ratios are much higher than 1, evidencing the dominance of the inorganic over organic forms of N.

Although DON concentrations were lower in rivers of the La Plata Basin, the TDN concentration was almost three times higher than that of rivers in the Amazon Basin because of the much higher DIN concentrations in the La Plata rivers (table 1). In contrast, the median DON concentrations of the Venezuelan small/medium watersheds (Tuy, Unare, Neveri, and Manzanares) were larger than those observed in the Amazon and Orinoco basins, accounting for about 30–50% of the TDN (table 1). In this case, the DIN:DON ratios indicate that inorganic N forms are predominant in watersheds influenced primarily by untreated wastewater (Tuy and Neveri), whereas organic N is predominant in the watershed influenced primarily by agricultural activities (Unare) (table 1). Compared to the three large basins evaluated, Tuy River had the highest TDN concentration (9808 $\mu g\ L^{-1}$), which was almost 12, 30, and 35 times higher than the median TDN concentrations of the La Plata, Amazon, and Orinoco basins, respectively (table 1).

The TDN yield of the Amazon River at Óbidos, the most downstream sampling site, was equal to

Table 1. Main characteristics and total dissolved nitrogen from Amazon, La Plata, and Orinoco basins and small and medium watersheds in northern Venezuela.

River	*N*	Q	DIN	DON	TDN	DIN: DON	DIN	DON	TDN	DIN	DON	TDN	Reference
		$m^3\ s^{-1}$	$\mu g\ L^{-1}$				$Gg\ yr^{-1}$			$kg\ ha^{-1}\ yr^{-1}$			
Amazon basin													
Solimões—Manacapuru	8	98 625	167	157	325	1.1	482.4	492.2	974.6	2.3	2.0	4.3	1
Amazon—Óbidos	8	157 142	185	141	325	1.3	850.8	731.6	1,582.4	1.9	1.6	3.5	1
Iça	8	7312	120	178	298	0.7	27	40	67	2.1	3.2	5.3	1
Jutaí	8	3425	29	276	305	0.1	3	29	32	0.4	4.0	4.4	1
Juruá	8	3737	191	176	368	1.1	20.5	23	44	1.1	1.3	2.4	1
Japurá	8	16 000	121	138	259	0.9	59.7	70	130	2.3	2.8	5.1	1
Purus	8	11 862	134	195	329	0.7	38.7	83	122	1.0	2.2	3.3	1
Negro	8	28 937	52	291	344	0.2	42.1	279	321	0.7	4.7	5.5	1
Madeira	7	25 879	185	141	326	1.3	134.7	119	254	1.0	0.9	1.9	1
Forest streams	30	0.50	108	192	300	0.6	2.9×10^{-6}	5.9×10^{-6}	9.0×10^{-6}	1.7	3.9	5.6	2,3
Pasture streams	27	0.14	109	198	307	0.6	1.1×10^{-6}	1.6×10^{-6}	2.7×10^{-6}	1.6	2.5	4.2	2,3
La Plata Basin													
Aguapei	18	80	743	34	777	22.0	1.3	0.4	1.7	2.2	0.7	2.9	1
Apiai	18	16	343	46	388	7.5	0.2	0.1	0.3	2.0	0.9	2.9	1
Atibaia	37	36	2048	3030	5078	0.7	1.0	1.4	2.4	3.7	5.4	9.0	1
Itapetininga	18	19	280	104	384	2.7	0.2	0.2	0.3	1.1	1.1	2.2	1
Jaguari	37	40	1081	1580	2661	0.7	0.8	1.2	2.1	2.9	4.3	7.2	1
Mogi-Guaçu	40	222	576	309	886	1.9	2.7	2.7	5.4	3.9	4.2	8.1	1
Paranapanema	18	23	390	44	433	8.9	0.3	0.1	0.4	3.8	2.1	5.9	1
Peixe	18	59	920	27	947	33.5	1.0	0.3	1.2	4.9	1.5	6.4	1
Piracicaba	59	107	1346	1356	2701	1.0	4.3	5.2	9.5	4.3	5.3	9.6	1
S.J. Dourados	18	27	625	40	665	15.7	0.4	0.1	0.6	2.3	0.6	3.0	1
Taquari	18	14	461	73	534	6.3	0.2	0.1	0.3	2.4	1.2	3.6	1
Turvo	18	26	993	49	1042	20.5	0.7	0.2	0.8	2.0	0.5	2.4	1
Venezuelan largest basin and small- and medium-sized rivers													
Tuy	27	53	6499	3309	9808	2.0	10.9	5.5	16.4	16.4	8.4	24.8	4
Neveri	25	17	1549	660	2209	2.3	0.8	0.4	1.2	2.8	1.2	4.0	4
Manzanares	30	20	278	297	575	0.9	0.2	0.2	0.4	1.1	1.1	2.2	4
Catatumbo	48	523	—	—	1269	—	—	—	20.9	—	—	8.2	5

Table 1. (Continued.)

River	*N*	Q	DIN	DON	TDN	DIN: DON	DIN	DON	TDN	DIN	DON	TDN	Reference
		$m^3\ s^{-1}$	$\mu g\ L^{-1}$				$Gg\ yr^{-1}$			$kg\ ha^{-1}\ yr^{-1}$			
Escalante	48	51	—	—	1902	—	—	—	3.1	—	—	6.0	5
Motatan	48	30	—	—	1460	—	—	—	1.4	—	—	2.9	5
Chama	48	52	—	—	2304	—	—	—	3.8	—	—	10.5	5
Santa Ana	48	180	—	—	368	—	—	—	2.1	—	—	9.5	5
Unare	28	21	1163	901	2105	1.3	0.8	0.6	1.4	0.3	0.3	0.6	4
Orinoco	—	38 000	115	160	275	0.7	137.8	191.7	329.6	1.5	2.1	3.6	6

Abbreviations: DIN, dissolved inorganic nitrogen; DON, dissolved organic nitrogen; Q, discharge rate; TDN, total dissolved nitrogen.
The numbers in the reference columns (Reference) represent: (1) Martinelli *et al* (2010), (2) Neil *et al* (2001), (3) Chaves *et al* (2009), (4) Rasse *et al* (2015), (5) Rivas *et al* (2009), (6) Lewis *et al* (1989, 1999).

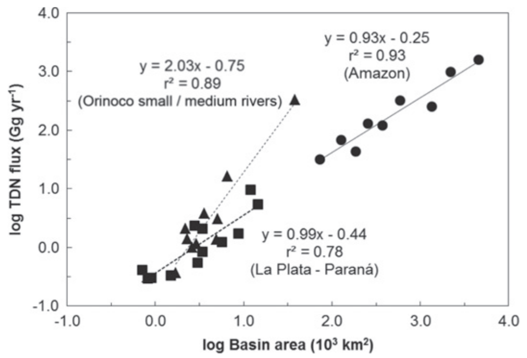

Figure 2. Relationship between the logarithm of the basin area and logarithm of the total dissolved nitrogen load (TDN) flux in rivers of South America, as assessed by linear regression correlation coefficients. Closed circles represent data from the Amazon Basin, closed squares represent data from the La Plata-Paraná Basin, and closed triangles represent data from Orinoco small/medium rivers.

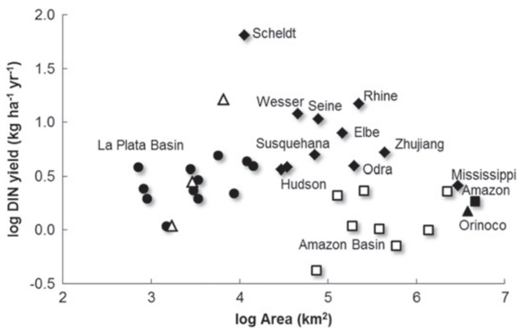

Figure 3. Relationship between the logarithm of the basin area and logarithm of the DIN yields. Closed square represents data from the Amazon river (Óbidos), open squares represent data from other rivers of the Amazon Basin, closed squares represent data from the La Plata-Paraná Basin (rivers of the State of São Paulo), closed triangle represents data from the Orinoco river, open triangles represent data from small- and medium-sized rivers of northern Venezuela, and closed diamonds represent data from major world rivers.

3.5 kg ha^{-1} yr^{-1} (table 1). Among the tributaries of the Amazon River, the TDN yields of black-water tributaries (Negro and Jutaí) were higher than those of white-water tributaries, primarily because DON contents were higher in these rivers (table 1). The TDN yield of the Negro River was 5.5 kg ha^{-1} yr^{-1}, which was considerably higher than the load of the Madeira River (1.9 kg ha^{-1} yr^{-1}) (table 1). TDN yields were also higher in the polluted rivers of the La Plata Basin and most of the small/medium Venezuelan rivers compared to rivers of the Amazon and Orinoco basins (table 1). In the La Plata Basin, TDN loads were higher in rivers of the Piracicaba Basin that are located in densely populated areas (Atibaia, Jaguari, and Piracicaba rivers) (table 1). In some small Venezuelan rivers, TDN yields were much higher, even compared with rivers of the La Plata Basin. For instance, the TDN yields of the Tuy and Catatumbo rivers were approximately 25 and 82 kg ha^{-1} yr^{-1} (table 1).

He *et al* (2011) compared rivers from different regions of the globe and found a direct relationship between water discharge and TDN load and yield. To compare rivers from basins of South America, we evaluated the relationship between the logarithm of the basin area and the logarithm of the TDN load (figure 2). We found significant correlations between these two variables in the rivers of the Amazon and La Plata basins ($p < 0.01$). The correlation coefficient for rivers of the Amazon Basin (0.93) was higher than correlation coefficients for rivers of the Orinoco Basin (0.89) and rivers of the La Plata Basin (0.78) (figure 2). The intercepts of the regression lines were similar, making it possible to compare the slopes for different river basins. The smallest regression line slope was observed for rivers of the Amazon Basin (approximately 0.9), increasing to approximately 1.0 for rivers of the La Plata Basin and 2.0 for Venezuelan rivers, although the last slope was not statistically significant (figure 2). These results suggest that as rivers pass from natural conditions to more disturbed conditions, the slope of the regression line between basin area and TDN load increases. In the La Plata Basin, Martinelli *et al* (2010) found that population density was a good predictor of TDN yield, probably because sewage is generally untreated in that region, and population density is a good proxy for sewage load in the river (Martinelli *et al* 2002).

To compare South American rivers with some of the most important rivers around the world, we plotted the logarithm of the basin area against the logarithm of DIN yields for major world rivers with available data (Meybeck 1982). Most of the major world rivers had high DIN yields compared with rivers of the La Plata Basin, and were especially high compared with rivers of the Amazon Basin (figure 3). The only South American river with a DIN yield similar to those of the major world rivers was the Tuy River in Venezuela (figure 3). Some of the major world rivers used in this comparison are located in densely populated areas; this was especially true for the European rivers. However, in European countries most urban sewage is treated, unlike the situation in South American countries. On the other hand, the use of N fertilizer per unit of area of arable land is much higher in Europe than in South America (Martinelli *et al* 2006). It is difficult with the available data to pinpoint the main causes for the lower TDN yields, especially for rivers of the La Plata Basin situated in densely populated areas, with most of the sewage load untreated before entering the rivers.

4. Organic matter inputs to South American rivers influence nitrogen dynamics

Labile organic matter inputs appear to modulate the N dynamics in rivers of South America through changes promoted by their decomposition. The decomposition process breaks down organic molecules using dissolved oxygen, producing carbon dioxide. As a consequence dissolved oxygen concentration decreases, and the DIN concentration increases (Ometto *et al* 2000). This organic matter load also interferes with N species distribution, affecting key processes modulating the N cycle (mineralization, nitrification, and denitrification). Here we discuss the effects of organic matter loads caused by forest–pasture conversion in two streams of the Amazon Basin and inputs of untreated domestic sewage in medium-sized rivers of the La Plata Basin and northern Venezuelan rivers.

In small streams of the Amazon, the changes are caused in part by the colonization of stream beds by grasses in pasture-converted areas (Neill *et al* 2001). This fresh input of organic matter decreases dissolved oxygen content through organic matter decomposition from approximately 6 mg L^{-1} in streams draining forest areas (forest streams) to <1 mg L^{-1} in streams draining pasture areas (pasture streams). This change in pasture streams likely increases denitrification; coupled with low nitrate input from pasture soils, this leads to a decrease in N content compared with forest streams (Neill *et al* 2001, Thomas *et al* 2004). Accordingly, we found that TDN yield decreased from 5.6 kg ha^{-1} yr^{-1} in forest streams to 4.2 kg ha^{-1} yr^{-1} in pasture streams (table 1).

The population densities in urban areas of the La Plata Basin are some of the highest in Brazil (www.ibge.gov.br/sidra). Streams that run through such densely populated areas are subject to a heavy load of untreated sewage (Martinelli *et al* 1999, Ometto *et al* 2000). The effects of this load on oxygen and N dynamics is exemplified by rivers of the Piracicaba River Basin, which is a typical medium-sized (12 000 km^2) watershed of the La Plata Basin. Although located in a highly economically developed area, these rivers are strongly affected by the load of untreated sewage (Martinelli *et al* 1999, Ometto *et al* 2000, Daniel *et al* 2002). In particular, the dissolved oxygen concentration is strongly affected by sewage load, which in turn affects N dynamics (Harrison *et al* 2005, Rosamond *et al* 2012). Nitrate concentrations are similar between polluted and nonpolluted sites of the Piracicaba Basin. However, ammonium concentrations are much higher in polluted sites, primarily because untreated urban sewage is rich in ammonium, and ammonium is not converted to nitrate via nitrification in areas with low dissolved oxygen. In addition, part of the nitrate is lost to the atmosphere via denitrification (Martinelli *et al* 1999).

In Venezuela 96.3% of the urban population is located in the central northern region of the country (Muñoz *et al* 2000, www.ine.gob.ve); therefore, agricultural nonpoint sources and urban sewage (mainly untreated) are the major anthropogenic sources of labile organic matter and N to watersheds and coastal areas of the Caribbean Sea (Rivas *et al* 2009, Rasse *et al* 2015). A previous study reported that N loads to coastal ecosystems are controlled primarily by seasonality, river topography, and the organic matter and N input of untreated wastewater (Rasse *et al* 2015). Water discharge during the rainy season is the main driver of N loads to coastal ecosystems. Topography affects the N load to coastal ecosystems, with mountainous rivers influenced by urban sources being a larger N source to the coast than lowland rivers (table 1). For instance, measurements were obtained over the course of a year from four rivers running into the Caribbean Sea in Northern Venezuela and with different topographies and anthropogenic impacts: the Tuy, Neverí, and Manzanares are small mountainous rivers with a range of urban influence, and the Unare is medium-sized lowland river influenced primarily by agricultural activities. The results showed that TDN load by all the rivers (19.3 Gg yr^{-1}) was derived mainly from untreated wastewater (23.3 Gg yr^{-1}), and to a lesser extent from agricultural nonpoint sources (8.2 Gg yr^{-1}). The fact that total TDN load (19.3 Gg yr^{-1}) was lower than the estimates of the untreated wastewater and agricultural nonpoint sources (31.5 Gg yr^{-1}) indicates that these watersheds have some buffer capability, allowing them to remove an important fraction of the N by nitrification and/or denitrification prior to delivery to the ocean. These results also indicate that TDN concentrations are highest during the dry season, whereas most (92%) of the annual TDN load to the coast occurs during the rainy season, demonstrating that water discharge is the most important factor controlling TDN dynamics in these watersheds. The TDN concentration and load values were one order of magnitude higher in the Tuy River, which is the most strongly affected by untreated wastewater from the Caracas metropolitan area, which at 22 Gg yr^{-1} represents approximately 94% of the total untreated point sources in all these rivers. The Tuy River also had the highest water discharge.

5. Challenges for nutrient management in Latin America

Constraining the generation and retention of nutrients from land to river systems to the coast at regional to continental scales remains a significant challenge. Management strategies should include incentives for using nutrients in agriculture appropriately for the optimum economic benefit, while minimizing the environmental impact. The promotion of sustainable agricultural intensification with effective nutrient management remains an important issue to meet the growing demand for food in the coming decades while minimizing negative effects on the environment and human health. Although studies have assessed ways to increase the N use efficiency of crops and decrease N losses in South American countries (García *et al* 2009), proven methods for mitigating N pollution from agriculture have not been widely applied (Austin *et al* 2013). Future studies on the mitigation of N losses are necessary to reduce the agricultural impact on the environment. However, development and dissemination of appropriate nutrient management recommendations for the region are hampered by the lack of spatially explicit information and poor monitoring of agricultural practices and soil conditions.

Despite the relevant role of agriculture in the region, water pollution is dominated by municipal discharges of domestic and industrial waste (UNEP 2001). Based on a business-as-usual scenario, inorganic N export to coastal systems is predicted to increase 3-fold by the year 2050 (relative to 1990) in Africa and South America (Kroeze and Seitzinger 1998, Seitzinger *et al* 2005). Besides human health problems, raw sewage results in deleterious effects on river composition. For instance, the presence of sewage N generally decreases species richness and increases the number of individuals of species more resistant to pollution (Ometto *et al* 2000). Recent studies in Brazil showed that although primary sewage treatment alleviates the input of labile organic matter to rivers, the N concentration remains practically unchanged, revealing that this type of sewage treatment is not sufficient to decrease N inputs (Daniel *et al* 2002, Bonini 2014). Therefore, it is imperative to increase the treatment of domestic sewage in the region. In 2008, 80% of the rural population and 97% of urban population had access to an improved water source; however, 23% (125 million) of people in the region had no access to improved sanitation (PAHO 2011). At present, watershed management strategies in South America are poorly implemented or nonexistent. Because wastewater represents the largest source of TDN to coastal ecosystems, increasing the number of wastewater treatment plants and optimizing the existing plants are critical strategies to effectively address the impact of N load on watersheds and coastal zones.

Nutrient management in South America must be an essential component of sustainable development and climate mitigation and adaptation. Although there are good examples of strategies that contribute to nutrient management on a local scale, efforts to control nutrient loads to inland and coastal waters at the watershed level are still restricted to a few areas. Multisectoral and regional approaches and adequate policy frameworks that consider land–water interactions are needed. However, the lack of spatial and temporal data on nutrient sources and the mobilization, distribution, and monitoring of effects (social, economic, and environmental) continues to be a major barrier.

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