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Human activities changing the nitrogen cycle in Brazil

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Abstract. The production of reactive nitrogen worldwide has more than doubled in the last century because of human activities and population growth. Advances in our understanding of the nitrogen cycle and the impacts of anthropogenic activities on regional to global scales is largely hindered by the paucity of information about nitrogen inputs from human activities in fast-developing regions of the world such as the tropics. In this paper, we estimate nitrogen inputs and outputs in Brazil, which is the world's largest tropical country. We determined that the N cycle is increasingly controlled by human activities rather than natural processes. Nitrogen inputs to Brazil from human activities practically doubled from 1995 to 2002, mostly because of nitrogen production through biological fixation in agricultural systems. This is in contrast to industrialized countries of the temperate zone, where fertilizer application and atmospheric deposition are the main sources of anthropogenic nitrogen. In Brazil, the production of soybean crops over an area of less than 20 million ha, was responsible for about 3.2 Tg N or close to one-third of the N inputs from anthropogenic sources in 2002. Moreover, cattle pastures account for almost 70% of the estimated 280×10^6 ha of agricultural land in Brazil and potentially fix significant amounts of N when well managed, further increasing the importance of biological nitrogen fixation in the nitrogen budget. Much of these anthropogenic inputs occur in the Brazilian savannah region (*Cerrado*), while more urbanized regions such as the state of São Paulo also have high rates of nitrogenous fertilizer inputs. In the Amazon, rates of anthropogenic nitrogen inputs are relatively low, but continuing conversion of natural forests into cattle pasture or secondary forests potentially add a significant amount of new nitrogen to Brazil given the vast area of the region. Better measurements of biological fixation rates in Brazil are necessary for improving the nitrogen budgets, especially at a more refined spatial scale.

Introduction

Over the past century, growing human population and increasing human activities related to the production of food and energy have more than doubled the production rate of reactive nitrogen (Nr) on the land surface of the Earth

(Galloway and Cowling 2002; Galloway et al. 2004) and greatly altered the nitrogen cycle globally. Consequently, in many parts of the world the conversion of unreactive N_2 to reactive forms (nitrogen oxides plus other oxidized nitrogen species, NH_3, NH_4, and organic N) became controlled mainly by anthropogenic activities such as fertilizer production, combustion of fossil fuel, and biological fixation in agriculture, instead of being controlled by natural processes such as natural biological nitrogen fixation (BNF) and lightning (Smil 2001; Galloway et al. 2004).

The anthropogenic production of Nr has been especially high in industrialized countries of the temperate zone, where severe eutrophication of estuaries and coastal zones (Howarth et al. 2000; NRC 2000; Rabalais 2002), acidification of lakes and streams (Vitousek and Field 1999), and forest decline (Aber et al. 1995, 2003) have become common environmental problems associated with increasing nitrogen loads to ecosystems. Because the tropics encompass mainly developing countries, the rates of Nr production by anthropogenic activities and inputs in tropical ecosystems have not been an issue commonly addressed in scientific investigations (Matson et al. 1999, 2002). However, important drivers responsible for the increased production of Nr in the temperate zone are increasingly influencing the nitrogen cycle in the tropics and sub-tropics (Matson et al. 1999; Galloway and Cowling 2002), further changing the global cycle. Therefore, advances in our understanding of the nitrogen cycle and the impact of anthropogenic activities at regional to global scales depend on the expansion of scientific studies of fast-developing regions of the world such as the tropics (Galloway et al. 2004).

Vast deforestation, rapid conversion of natural vegetation into agricultural lands accompanied by intensification of agriculture, expansion of nitrogen-fixing crops, increasing rates of fertilizer consumption, population growth and fast urbanization rates are the common drivers altering the nitrogen cycle in the tropics. For instance, deforestation and slash-and-burn practices in the Amazon basin, where forest clearings have reached about 250,000 km^2 between 1990 and 2003 (Laurance et al. 2004), alters the nitrogen cycle by increasing the rates of nitrogen mineralization and mobilization in soils and, consequently, the export of nitrogen in tropical streams (Williams and Melack 1997). After the typical conversion of Amazon forests into pastures, rates of mineralization and nitrification tend to decrease, and reduce the nitrogen availability in soils and delivery rates to water bodies (Neill et al. 1997; Melillo et al. 2001). However, as natural vegetation and aging pastures are increasingly converted to intensive production of export crops such as soybeans, cotton and other lucrative crops, growing rates of both nitrogenous fertilizer consumption and biological nitrogen fixation in agriculture (Boddey et al. 1997) are leading to increased inputs of anthropogenic Nr to the landscape and, eventually, to higher export of nitrogen to surface waters (Downing et al. 1999).

In this paper, we examine the changes in the nitrogen cycle associated with anthropogenic activities in Brazil, the largest tropical country in the world, with 8.5 million km^2 and a wide range of tropical biomes, spanning from humid tropical lowland forests to dry tropical forests, savannas, wetlands and mountain forests. The main large-scale activities changing the nitrogen cycle in Brazil include deforestation of the Amazon, the conversion of vast areas of pastures and natural vegetation to high-intensity agriculture in the central region (*Cerrado*), and high urbanization rates in the southeast region, where urban centers such as Rio de Janeiro and São Paulo have approximately 12 and 18 million people, respectively.

Methods

The effects of human activities on the nitrogen cycle in Brazil are examined using a nitrogen budget approach for large regions (Howarth et al. 1996), and where new net anthropogenic nitrogen inputs (net inputs = inputs – outputs) are quantified and subtracted from outputs and compared with riverine exports (Boyer et al. 2002). We quantify anthropogenic nitrogen inputs for the whole country as well as for some contrasting regions that represent its largest biomes and/or where changes are occurring at the fastest pace. New nitrogen refers to reactive nitrogen (Nr) that is either newly fixed within or transported into a region. New net nitrogen inputs in the budget include NO_y ($NO_y = NO_x$ ($NO + NO_2$) plus other single N species with an oxygen atom), and NH_x ($NH_x = NH_3$ plus aerosol NH_4^+) (Galloway et al. 1995) from atmospheric deposition, nitrogen from fertilizer application, biologically fixed nitrogen in agriculture, and imports of foodstuffs.

In nitrogen budgets constructed for other large countries such as the US (Howarth et al. 2002), it has been assumed that the N status of soils is in steady sate and that the rate of soil-N mineralization equals the rate of nitrogen immobilized on an annual basis, at least on a several year period. In the present study, we also assume that soil N is in steady state. However, because mineralization of nitrogen occurs on such a large scale in Brazil due to deforestation and biomass burning in the Amazon (Williams and Melack 1997) and central region, this assumption needs to be considered with caution because newly mineralized nitrogen from the Amazon forest may function like a new input from anthropogenic activity in the region, especially in aquatic ecosystems.

Data sources

Nitrogen inputs from fixation in agricultural land in Brazil were estimated as the product of the total area of land planted with major crops (i.e., soybeans, common beans, sugarcane) and pasture associated with BNF, and the average fixation rates available in the scientific literature for each one of these agricultural land types, as described below. Land use data for soybeans, pastures, common beans and sugarcane were obtained from the Brazilian Institute of

Geography and Statistics, IBGE (2004). Additional data on land use area of pastures and common beans were obtained from Boddey et al. (2003) and Mostasso et al., (2002), respectively.

Nitrogen fertilizer inputs for Brazil were estimated from several sources, including the Brazilian National Agency for Distribution of Fertilizers (ANDA), the International Potash Institute (POTAFOS-Brasil), and the International Fertilizer Industry Association (IFA). Fertilizer data from the Food and Agriculture Organization of the United Nations (FAO) were excluded from our budgets because their values were consistently low in comparison to those from all the other data sources such as ANDA, POTAFOS, and IFA.

Except for some data on wet deposition for the Central Amazon (Lesack and Melack 1991; Williams and Melack 1997; Filoso et al., 1999) and southeastern Brazil (Lara et al. 2001), N deposition (NH_x and NO_y) in the country is essentially unknown. Therefore deposition of N in Brazil and regions presented here was based on model simulations for global N deposition in the early 1990s as described in Dentener and Crutzen (1994) and Lelieveld and Dentener (2000), and extensively used by Galloway et al. (2004), Rodhe et al. (2002), Seitzinger et al. (2002), and Neff et al. (2002). However, in order to obtain deposition data for Brazil, the model had to be modified to simulate deposition in South America. Some of the uncertainties associated with using the global model for a region of the globe are discussed in Galloway et al. (2004).

Inputs

Inputs from fixation in agriculture

Over the past 40 years, the agricultural area of Brazil has expanded over 100 million ha, at a rate of almost 3 million ha yr^{-1} (Figure 1). Much of this

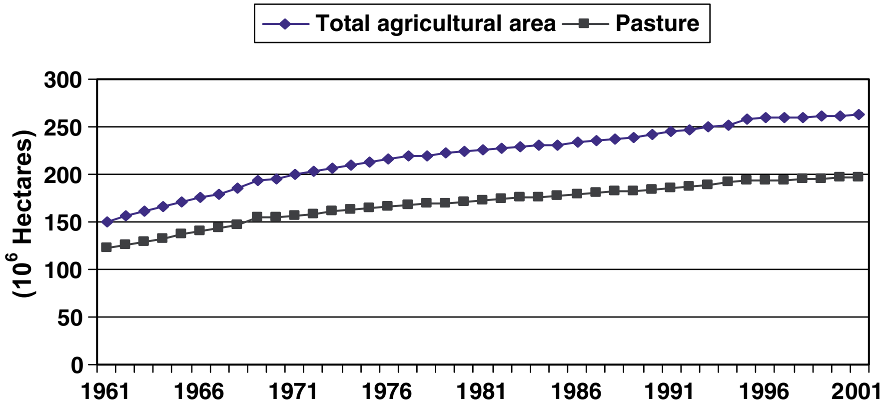


Figure 1. Total agricultural area, and total pasture (natural and introduced) between 1960 and 2002 (FAOSTAT 2004).

expansion occurred due to increasing areas of improved or cultivated pastures for cattle ranching but, in the past decade, the area of annual crops in Brazil has grown at a faster rate than the area of pastures (FAOSTAT 2004). One of the main causes for the rapid expansion of field crops in recent years has been the growth of soybean cultivation in the country, which was partially promoted by advances in the Brazilian soybean-breeding program that lead to the spread of the crop from high to low latitudes and, consequently, to new land entering production in the Brazilian *Cerrado* region (Alves et al. 2003; Machado et al. 2004).

Soybeans need large quantities of nitrogen for plant growth and development, but because Brazilian soybeans are able to obtain between 70 and 85% of the nitrogen required from biological fixation (Alves et al. 2003; Boddey et al. 1991), nitrogen fertilizer is not commonly applied to soybean fields in Brazil. Therefore, the only source of anthropogenic N in Brazil associated with the growing soybean production in the country is biological nitrogen fixation (BNF), as opposed to the U.S. and other countries of the temperate zone, where N fertilizer is often applied in soybean fields.

On average, the productivity of soybeans harvested in Brazil is 2400 kg ha^{-1} yr^{-1} and the BNF rates range between 70 and 250 kg N ha^{-1} yr^{-1} (Alves et al. 2003). Therefore, if we assume an average rate of 170 kg N ha^{-1} yr^{-1}, the cultivation of this crop in Brazil potentially introduced about 2.5 Tg of Nr to the Brazilian and global budgets in 1995, which is equivalent to more than 6% of the amount of nitrogen produced by BNF in agriculture worldwide according to estimates for the mid 1990s by Galloway et al. (2004). In 2004, with 22.9 million ha planted with soybeans in Brazil, the creation of reactive nitrogen via fixation in agriculture potentially reached close to 4 Tg N.

Soybean cultivation is the activity most commonly associated with BNF in agriculture in Brazil. However, two other agricultural activities in the country have been shown to produce significant amounts of reactive nitrogen via BNF; one is the cultivation of sugar-cane (Boddey et al. 1991; Doberheiner 1997) and the other is the cultivation of pasture grasses. BNF in pastures can be especially important for the nitrogen budget in Brazil because of the large extent of this type of land use in the country. According to estimates FAOSTAT (2004), Brazil has about 265 million ha of agricultural land, of which 197 million consists of permanent pastures (Figure 2). Most of these pastures have been formed in the past 30 years, when tropical forests and savannas were replaced with exotic grasses of African origin, especially *Brachiaria* spp. (Boddey et al. 1997). Approximately 80 million ha of *Brachiaria* spp. is now planted in Brazil (Boddey et al. 2004), and several ecotypes of *Brachiaria* spp. and of *Panicum maximum*, another representative type of grass in the region, have been shown to obtain between 40 and 50 kg N ha^{-1} yr^{-1} from plant-associated BNF in field experiments (Boddey and Victoria 1986; Miranda and Boddey 1987), while different species of *Pennisetum* can derive up to 165 kg N ha^{-1} yr^{-1} from BNF. This nitrogen comes mainly from non-symbiotic associations with endophytic bacteria or from bacteria in the rhizophere.

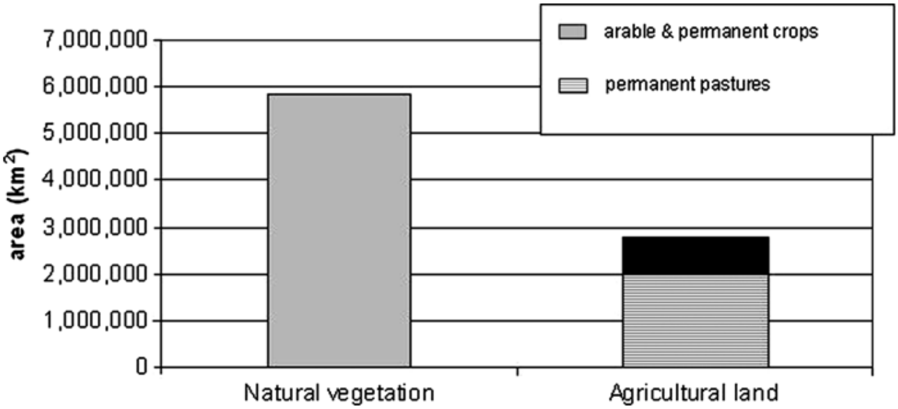


Figure 2. Comparison of natural and agricultural land cover areas in Brazil in 2002.

Fixation rates have not been measured in pastures under grazing, but we assume that they are relatively low (~15–30 kg N ha^{-1} yr^{-1}) even under N limitation conditions, because of limitation of P and other nutrients, as well as because of drought periods during the dry season in regions such as the Brazilian *Cerrado* where much of the pastures are situated (S. Urquiaga, personal communication, EMBRAPA, Brazilian Agency of Agriculture and Pecuary). Another factor that can limit BNF in pastures in Brazil is overgrazing (and consequent degradation), which occurs in about 50% of this land type in the country (Boddey et al. 2004). Therefore, if we assume that BNF is occurring at a conservative rate of 15 kg N ha^{-1} yr^{-1} in 50% of pasture land of Brazil (except for the Amazon where we use a rate of 30 kg N ha^{-1} yr^{-1} as explained below), we can predict that pastures in Brazil potentially create about 3.4 Tg N yr^{-1} in the regional budgets, which is a significant quantity at the global scale (Table 1).

The third most common type of field crop in Brazil associated with BNF is sugar-cane, which accounts for about 5 million ha of the agricultural land of the country. Sugarcane has been cultivated in Brazil since the 16th century under low nitrogen fertilizer inputs, while depletion of soil-nitrogen reserves has not been commonly observed, possibly because of inputs of biologically fixed nitrogen by the sugarcane (Yoneyama et al. 1997; Boddey et al. 2003). Recent field studies with ^{15}N abundance in sugarcane fields planted with commercial varieties have shown that BNF contributes between 0 and 60% of plant N (Boddey et al. 1991, 2003). Sugar-cane in Brazil, commonly, accumulates an average of 110 kg N ha^{-1} (Oliveira et al. 1999), while non-symbiotic N fixation can contribute between 0 and 66 kg N ha^{-1} yr^{-1} (Urquiaga et al. 1992) which is 0 to 0.33 Tg N of the regional and global budgets. While these numbers are relatively low and not significant at a large scale, BNF in sugar-cane can be a very important constituent of nitrogen budgets at the watershed scale where monoculture of sugar-cane is widespread, such as in the Southeast Brazil (Filoso et al. 2003).

Table 1. Nitrogen inputs in Brazil from natural and anthropogenic sources during the pre-colonization, in 1995 and 2002.

Nr Sources	Brazil			Latin America	North America	Global
Natural	1500	1995	2002	1995	1995	1995
Natural BNF	17.1	11.6	10.9*	26.5	11.9	107
Lightning	0.5	0.5	0.5	1.4	0.2	5.4
Total	17.6	12.1	11.4	27.9	12.1	112
Anthropogenic						
Fertilizer use	0	1.2	2.5	3.9	12.7	77.6
BNF in agriculture	0	3.5	7.3	5.0	6.0	31.5
Fossil fuel combustion	0	0.4	0.7	1.3	7.3	24.5
Net imports of foodstuffs	0	−0.1	−1.1	−0.9	−3.0	
Total	0	5.0	9.4	9.3	23.0	134

Values for Latin America, North America and Global are adapted from Galloway et al. 2004. Nitrogen inputs are estimated in Tg yr^{-1}.

*Value for natural BNF in 2002 was estimated using the same data for land cover of natural vegetation in Brazil for the mid 90s minus the amount fixed in the area lost to agricultural lands in the *Cerrado* and Amazon during the period between mid 90s and 2000, according to estimates from INPE (2004) for the Amazon, and from Machado et al. (2004) for the *Cerrado*.

Inputs from fertilizer use

Although much of the expansion of intensive agriculture in Brazil in the last decade has been associated with soybean crops in the *Cerrado* region, other crops such as cotton, maize, sunflower and sorgum have been expanding together with soybeans, especially in the past few years (Machado et al. 2004). The *Cerrado* is composed of highly leached, acidic soils, and have low levels of P and N availability (Bustamante et al. 2004). Therefore, large quantities of lime and fertilizer, including nitrogenous, are required for crops not associated with BNF. Consequently, the agricultural expansion that has occurred in Brazil in the past few years has been accompanied also by the growth of nitrogen fertilizer consumption.

The consumption of nitrogen fertilizer in Brazil increased about 30 times from 1960 to 2002 (Figure 3), from about 0.07 to about 2.5 Tg N yr^{-1} (ANDA 2003; POTAFOS-Brasil 2004). But one of the largest and most rapid increases in the use of nitrogenous fertilizer in the country began in the late 1990s, which also coincides with a period of great agricultural expansion in the *Cerrado* region. According to predictions for the next few decades, the area of intensive agricultural crop production in Brazil, not including the Amazon region ($\sim$60% of the Brazilian territory), will expand by about 170 million ha, and much of this is projected to take place in the *Cerrado* region (USDA 2003). For the N budget in Brazil, this expansion in the nutrient-poor soils of the *Cerrado* means a considerable increase of nitrogen fertilizer consumption and, possibly, higher delivery rates of reactive N to aquatic systems.

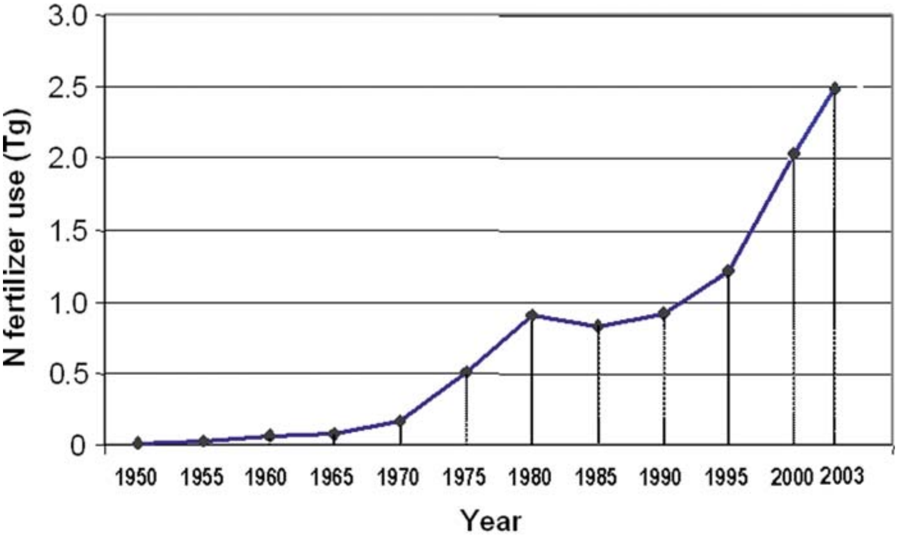


Figure 3. Consumption of nitrogen fertilizer along a period of 40 years in Brazil (Source: SIACES/POTAFOS-Brasil 2003; ANDA 2003).

Inputs from atmospheric deposition

As stated above, deposition of N in Brazil presented here is based on model simulations of global N deposition in the early 1990s described in Dentener and Crutzen (1994) and modified for South America. According to the model simulations for the 1990s, NO_y deposition in most of Brazil varies between 100 and 250 mg m^{-2} yr^{-1} (Figure 4), but along the coast on the North and Northeast region, deposition is lower, varying between 50 and 100 mg m^{-2} yr^{-1}. A few areas with deposition rates up to 500 mg m^{-2} yr^{-1} are clearly associated with highly urbanized and industrialized regions of the country such as São Paulo state, in agreement with data collected in the region in the late 90s (Lara et al. 2001). Overall, assuming an intermediate deposition rate of 175 mg m^{-2} yr^{-1} for the whole country, total deposition of NO_y over Brazil amounts to 1.4 Tg N yr^{-1} (Table 1).

Deposition of NH_x in Brazil is less homogeneous than deposition of NO_y, and a strong gradient can be observed for rates between the southern and northern regions of the country (Figure 5). The highest deposition rates have been estimated for the South and Southeast, where intensive agricultural activities are prevalent. In these regions, deposition of NH_x varied between 500 and 2000 mg m^{-2} yr^{-1} (Figure 5), while in much of the Amazon rates were below 100 mg m^{-2} yr^{-1}. The modeled values fall in the range of the few available measurements of deposition of NH_4 in the Amazon and São Paulo state. We assumed an average deposition rate of 250 mg m^{-2} yr^{-1} for the whole country and estimated that the total deposition of NH_x is on the order of

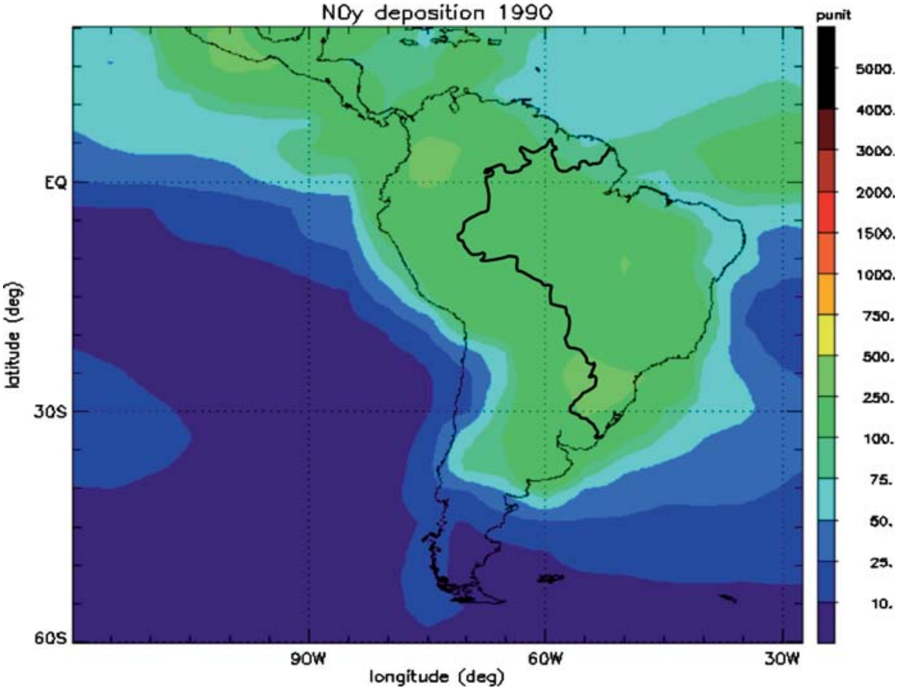


Figure 4. Modeled NO_y deposition in Brazil in the mid 90s. Results were generated by the TM3 global chemistry-transport model of the University of Utrecht on a 5° by 3.75° grid.

2.1 Tg N yr^{-1}, compared to 4.4 Tg N yr^{-1} for South America and 56.7 Tg N yr^{-1} globally (Galloway et al. 2004).

By performing a marked tracer experiment, as described in Lelieveld and Dentener (2000) and Marufu et al. (2000), the origin of these depositions was estimated in relative proportions, and showed that fossil fuel combustion contributed between 20 and 50% of the NO_y emissions along the eastern portion of Brazil, from North to South, while in the central region (*Cerrado*) and the Amazon basin fossil fuel emissions contributed less than 20% of the total NO_x inputs (Figure 6). These estimates are in accordance with population densities in Brazil, which are the highest along the coastal region and the lowest in the Amazon basin. Natural soil emissions contribute the largest percentage of NO_y deposition in the Amazon basin, while biomass burning emissions are becoming increasingly important. In the central region, biomass burning contributes up to 70% of the NO_y deposition probably because of natural and anthropogenic fires that occur mainly in the dry season.

The association of relatively high rates of NO_x emission from fossil fuel with more densely populated areas of the country is partly due to the fact that NO_x emissions in Brazil originate mainly from petroleum products used in on-road vehicles (Figure 7). The consumption of fossil fuel for production of electric

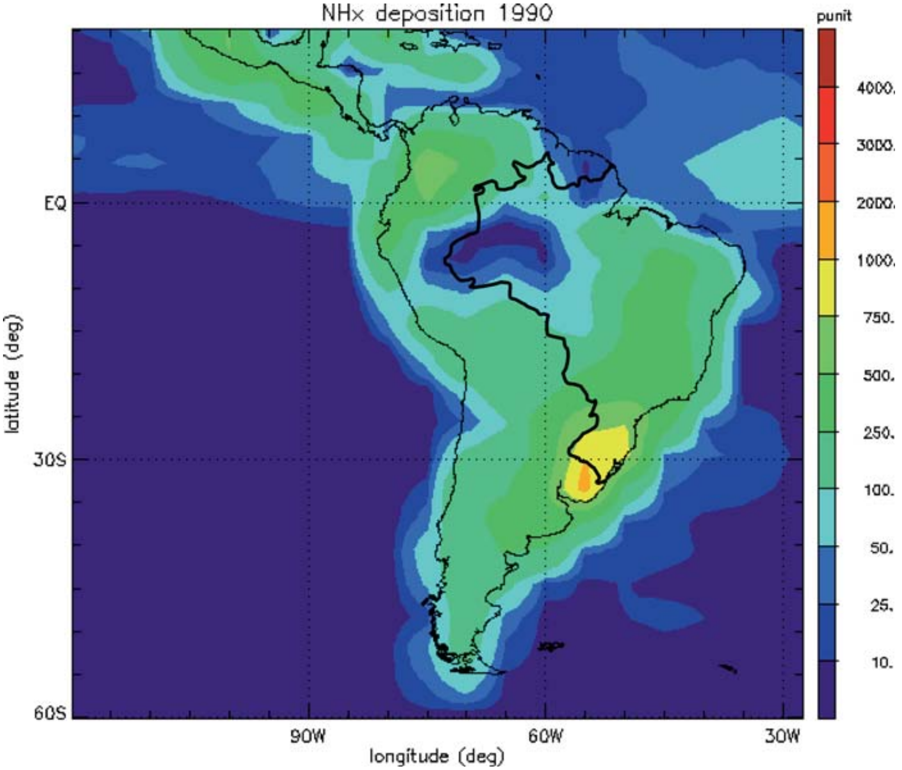


Figure 5. Modeled NH_x deposition in Brazil in the mid 90s. Results were generated by the TM3 global chemistry-transport model of the University of Utrecht on a 5° by 3.75° grid.

energy is negligible. Moreover, emissions from coal burning are insignificant since most of the electrical energy produced in the country comes from hydroelectric power plants.

Anthropogenic sources of NH_x emissions estimated by the model include fertilizer application and animal waste, and together are responsible for 70–90% of the deposition along the eastern portion of the country. In the central and western regions, including the Amazon basin and the central-west, anthropogenic sources contribute, on average, about 30 to 40% of the NH_x deposition (Figure 8a), while emissions from biomass burning are dominant (Figure 8b). Some of the biomass burning is caused by natural fires, especially in the central region of Brazil (Pinto et al. 2002). However, most of the biomass burning is associated with anthropogenic activities such as deforestation and pasture management practices and lead to high amounts of mineralized N in the ecosystems.

Since part of the NH_x deposited in Brazil originates from fertilizer, cattle manure, and biomass burning of agricultural fields such as sugar cane, or even from volatilization of NH_3 from senescing sugar cane plants, it is likely that

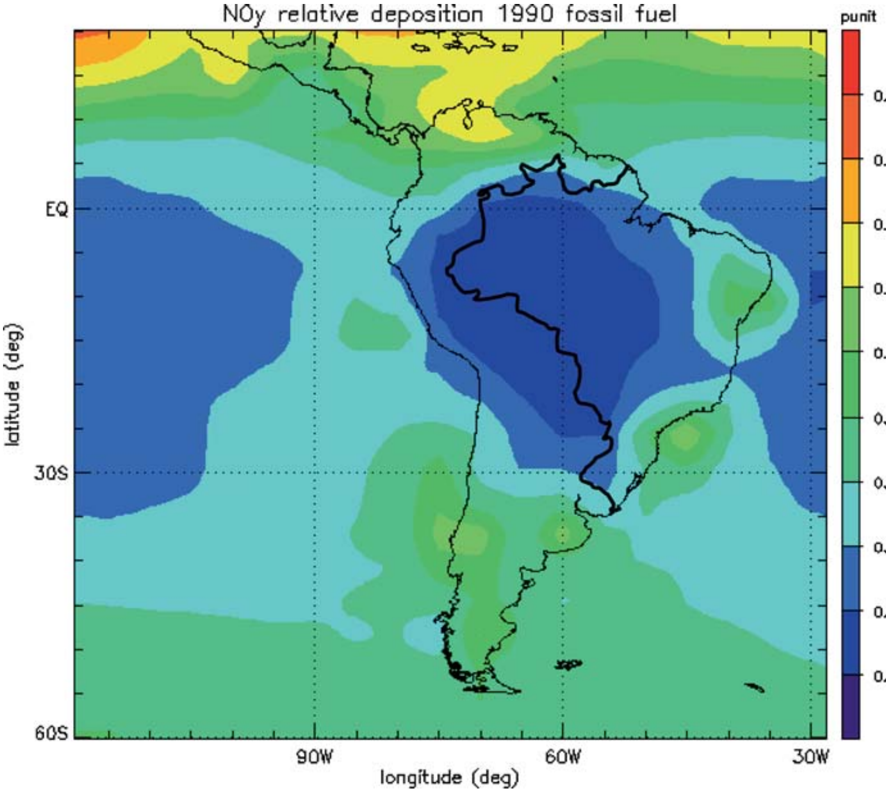


Figure 6. Modeled relative deposition of NO_x in Brazil from fossil fuel emissions in the mid 90s. Results were generated by the TM3 global chemistry-transport model of the University of Utrecht on a 5° by 3.75° grid.

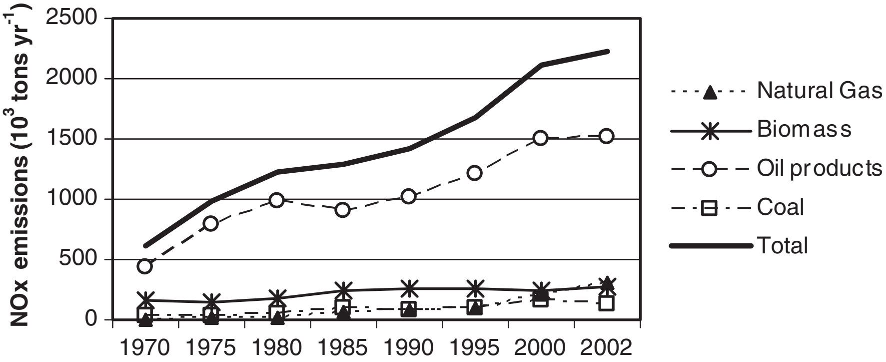
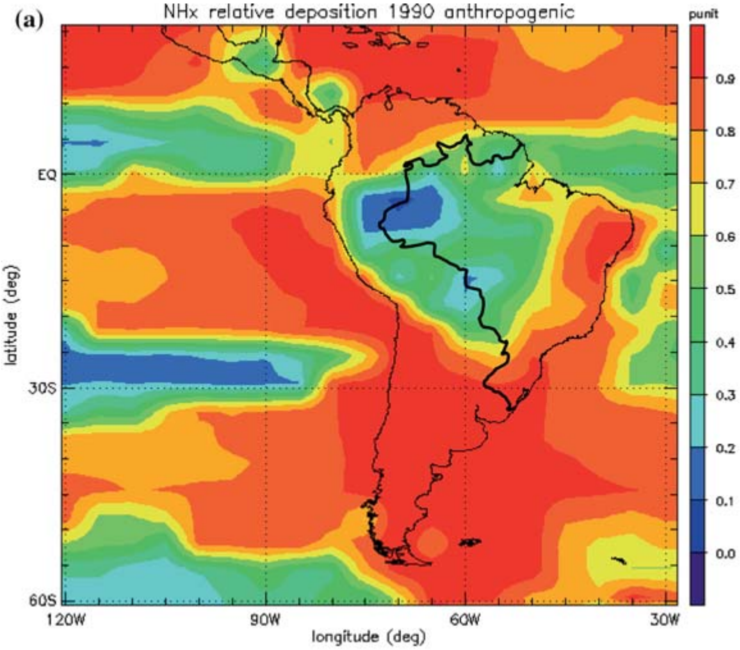


Figure 7. Emissions of NO_x in Brazil from different sources between 1970 and 2002 (Source: Brazilian Ministery of Science and Technology – http://www.mct.gov.br).


(a)
NHx relative deposition 1990 anthropogenic
punit
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
EQ
30S
60S
latitude (deg)
120W
90W
60W
30W
longitude (deg)

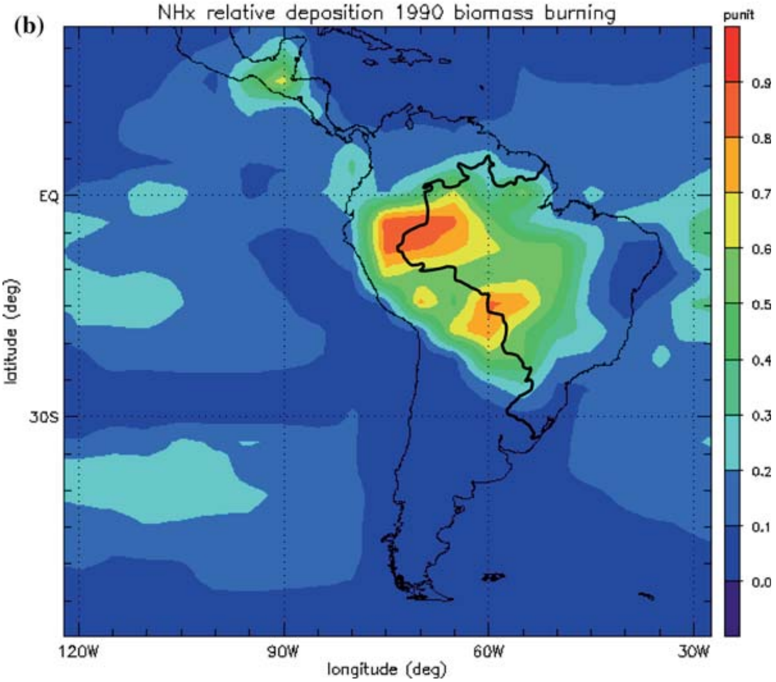

(b)
NHx relative deposition 1990 biomass burning
punit
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
EQ
30S
latitude (deg)
120W
90W
60W
30W
longitude (deg)

Table 2. Import and export of N in Brazil in foodstuffs for 2002.

	N import Tg yr^{-1}	N export Tg yr^{-1}	Source
Cereals	0.136	0.01	Smil 1999
Starchy roots	0.001	0.0004	Smil 1999
Sugar & sweets	0.000	0.043	Smil 1999
Beans	0.006	0.001	Smil 1999
Treenuts (forage)	0.000	0.000	Smil 1999
Soybeans	0.072	1.099	Alves et al., 2003
Veg/fruits	0.001	0.023	Smil 1999
Coffee	0.013	0.070	Smil 1999
Beef	0.000	0.028	Boddey et al. 2004
Pig meat	0.002	0.017	Smil 1999
Poultry meat	0.000	0.069	Smil 1999
Fish/seafood	0.00	0.00	Smil 1999
Milk	0.002	0.001	http://www.leco.org
Forage	0.005	0.00	Smil 1999
Total	0.24	1.36	

Note: Values of N exported and imported in Brazil through the different food types listed have been indirectly estimated from the sources cited.

some of the N in NH_x deposition may be double counted in the budget. This might also be true for NO_y if some of it comes from the burning of improved pastures which fix N. However, atmospheric deposition contributes small amounts of N to the total budget and, therefore, errors generated from uncertainties associated with N deposition data should be minor.

Outputs

Exports of N in food and feed

Brazil has the largest economy in Latin America, a population of over 174 million people increasing at 1.38% per year, and a consequent positive influence on the demand for food. Overall, most food and feed consumed in Brazil originate in the country itself, although Brazil imports some products such as cereals, oil seeds, some fruits, fish and seafood, and milling products like malt, starch and wheat gluten (Agriculture and Agri-food Canada 2004). Because the amount of these imported products to Brazil is relatively small (FAOSTAT 2004) and/or their N contents low (Smil et al. 1999), the amount of N imported with these food products is unimportant (Table 2).

Figure 8. (a) Relative importance of NH_x deposition in Brazil from anthropogenic sources based on the TM3 global chemistry model-simulated results. (b) Relative importance of biomass burning in the deposition of NO_x in Brazil in the mid 90s. Results are based on simulated values produced by the TM3 global chemistry model.

In contrast, a significant amount of N in agri-food products produced in Brazil is exported to foreign countries, especially to the Netherlands, USA, Russia, Germany and China (Agriculture and Agri-food Canada 2004). The main products exported are soybeans, soybean oil, sugars, fruits, meat, and coffee (FAOSTAT 2004) and the N exported with these products is approximately 1.36 Tg N yr^{-1} (Table 2). Therefore, the net import of N to Brazil from food and feed is negative (Table 1).

Between 1995 and 2002, the net export of N in foodstuffs from Brazil increased about one order of magnitude, from about 0.1 to 1.1 Tg N yr^{-1} (Figure 9). This increase was caused mainly by growing exports of soybeans, while importation of cereals, the largest imported food product in Brazil, remained quite constant throughout the years.

Export of N in wood and other products

The most important forest (wood) products exported in Brazil in terms of quantity are sawnwood and chips/particles, with approximately 2×10^6 m^3 exported annually between 1995 and 2002 (FAOSTAT 2004). Most of the exported material is produced in the Amazon basin, where about 4.5×10^6 m^3 of wood is extracted annually. Assuming that logging in the Amazon basin averages 25–30 m^3 ha^{-1} (Keller et al. 2004), and that the export of N from selective logging is on the order of 200 kg ha^{-1} (Martinelli et al. 2000), we estimate that N export from Brazil in wood products is about 0.36 Gg. In comparison to foodstuffs, the export of N in wood products is significant for

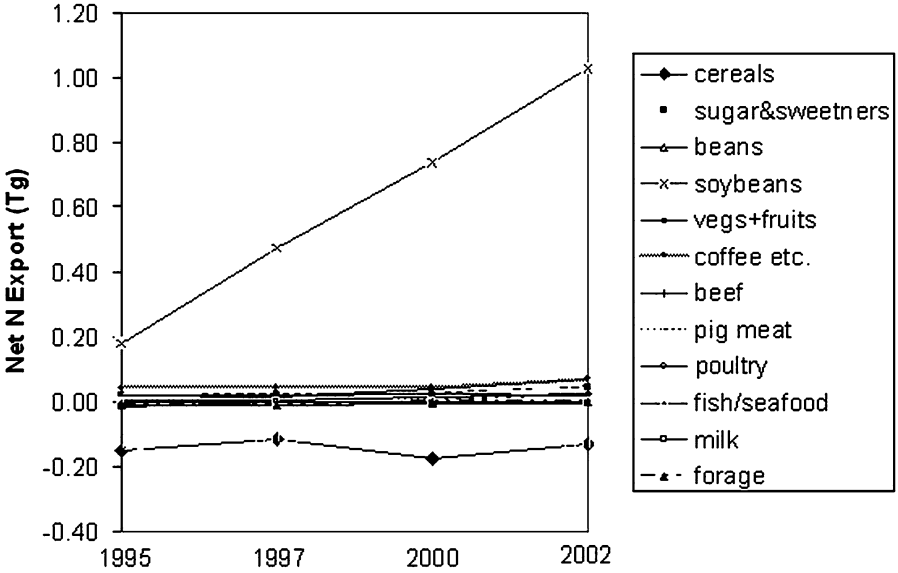


Figure 9. Net export of N from Brazil in foodstuffs in 1995, 1997, 2000, and 2002.

the country as a whole. However, such losses can be significant on a regional scale in the Amazon basin, especially because it is a cumulative loss.

In the South and Southeastern Brazil, the production of wood, mainly from silviculture, is also considerable but the wood produced there is mostly used in the Brazilian industry of paper and cellulose and consumed within Brazil (FAOSTAT 2004). Therefore, we consider that the N export in wood products from other regions of Brazil besides the Amazon is not significant.

Riverine export of Nr to Atlantic Ocean

Annually, world rivers discharge an average of 42×10^3 km^3 of freshwater into oceans (ANA 2004). Rivers in Brazil contribute about 20% of the global discharge, mainly because of the Amazon River, which supplies an average of 6.5×10^3 $\mathrm{km}^3\ \mathrm{yr}^{-1}$ of water to the Atlantic Ocean, and makes Brazil the country with the largest volume of freshwater discharged into oceans ($\sim 8.2 \times 10^3$ $\mathrm{km}^3\ \mathrm{yr}^{-1}$) (AQUASTAT 2004; ANA 2004). Other major Brazilian watersheds, according to the Brazilian Water Agency (ANA) are the Tocantins, North and Northeast Atlantic, Parnaíba, São Francisco, East Atlantic, Paraguay, Paraná, Uruguay, and South and Southeast Atlantic (Figure 10); they range in size from 178 to 1029 km^2 and generate 41 to 372 km^3 of water annually within Brazil (ANA 2004).

Although Brazil has such an abundance of water resources, more than 73% of the freshwater available in the country is located in the Amazon basin, where it is used by less than 5% of the population (ANA 2004). The remaining

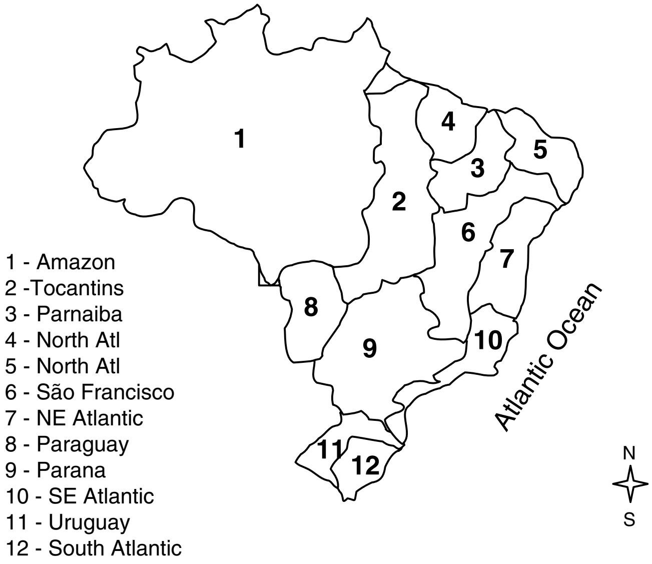


Figure 10. Map of Brazil with the delineation of the major river basins in the country (ANA 2004).

Table 3. Nitrogen export in major rivers in Tg yr^{-1}.

	DIN	TN	Data source
Amazon	0.96	3.0	Lewis et al. (1999)
Tocantins/Araguaia		0.3	Howarth et al. (1996)
Paraná	0.14	0.21	Bonetto et al. (1991)
Paraguay		0.03	Lewis et al. (1999)
TOTAL		3.54	

DIN – dissolved inorganic N, and TN – total N.

27% of the water available is produced in the 11 other major watersheds, and used by 95% of the country's population (ANA 2004) for water supply, agriculture, industry and production of hydroelectric power.

Because of its high water volume, the Amazon River is the single largest source of nitrogen to the Brazilian coast, transferring approximately 3 Tg N yr^{-1} from land to ocean annually (Table 3), with 0.96 Tg N yr^{-1} in dissolved inorganic form. The Amazon basin is still considered pristine, but increasing deforestation and agriculture expansion in the region are likely to cause major impacts on the N-cycle and maybe increase nitrogen transport into aquatic systems (Downing et al. 1999). The Tocantins River watershed is another important drainage system in the Amazon region, with a drainage area of 767,000 km^2 and annual mean discharge of 11,000 m^3 s^{-1} (Costa et al. 2003). However, the export of nitrogen in this river is approximately 0.3 Tg N yr^{-1}, or only 10% of that of the Amazon River, based on estimates presented in Howarth et al. (1996) (Table 3).

The Paraná watershed is the second largest drainage system in Brazil and accounts for 75% of the water discharge at the mouth of the Rio de la Plata. Although only about half of the Paraná River watershed is situated in Brazil, the Brazilian portion drains a region that is densely populated, has vast areas of intensive agriculture, and is highly industrialized. Human impacts in this part of the watershed have severely altered the nutrient dynamics in the entire Paraná River (Bonetto et al. 1991), including the deposition of phosphorus (P) and suspended sediments promoted by man-made reservoirs in the basin, the concomitant decrease in P concentrations coupled with P limitation (Bonetto et al. 1991; Villar et al. 1998), and the increase of N export in the past few decades (Bonetto et al. 1991). Pedrozo and Bonetto (1989) have claimed fertilizer inputs contribute the greatest share of nitrogen inputs into the Paraná basin, although only a small percentage of the inputs are accounted for in the riverine export at a sampling station located approximately 350 km below Iguaçu Falls (Bonetto et al. 1991). At this point in the main stem of the Paraná River, export rates of inorganic N average 188 kg N km^{-2} yr^{-1}, or 0.49 Tg N yr^{-1} (Table 3), and concentrations range between 0.06 and 1.4 mg l^{-1}, with nitrate accounting for 74% of the pool (Bonetto et al. 1991). Closer to the border of Brazil with Paraguay and Argentina, DIN concentrations are on the order of 0.4 mg N l^{-1} (Bonetto et al. 1991), which would result in the export of about 0.14 Tg DIN yr^{-1}. No data are available for TN concentrations in the Paraná River at the border of Brazil, but if we assume that the export of DIN in tropical rivers is roughly about two-thirds that of TN, according to the data presented in Lewis et al. (1999), then we can estimate that the export of N in the Parana River at the Brazilian border is approximately 0.21 Tg N yr^{-1}.

The Paraguay River drains about 140,000 km^2 of the great Pantanal wetland in Brazil, and has a wide surface of floodplains which are inundated during flood periods and undergo anoxia, promoting N losses by denitrification (Bonetto et al. 1991). Therefore, N limitation has been commonly observed in the Paraguay River (Bonetto et al. 1991; Villar et al. 1998), and the riverine N exports in Brazil are not likely to amount to more than about 0.03 Tg N yr^{-1} (Lewis et al. 1999).

The export of nitrogen in the remaining major watersheds in Brazil is not presented here because of unavailability of N concentration data for most rivers. Discharge data are widely available for Brazilian rivers as they are commonly monitored for their high potential for hydroelectric energy production in the country. However, water quality monitoring has been limited to a few rivers, mostly in the state of São Paulo, where water pollution has become a major issue.

Even without a complete estimate of the total amount of nitrogen that is exported from Brazil in all rivers both discharging into the Atlantic Ocean or flowing to neighboring countries, we speculate that the total riverine nitrogen export in Brazil is not likely to differ widely from the combined value for the Amazon, Paraná, Paraguay and Tocantins rivers (Table 3), because these rivers account for most of the water discharge in the country. Therefore, we estimate that the total riverine export of nitrogen in Brazil approximates 3.5 Tg N yr^{-1} (Table 3), which is 42% or more of the total N inputs in the country from anthropogenic sources (Table 1). The percent export of N in Brazil is higher than those observed for countries of the temperate zone probably because of the naturally high water flux rates observed in the Amazon River.

Nitrogen inputs vs. outputs in Brazil

Overall, we estimate that net inputs of anthropogenic N to Brazil in 2002 were 9.4 Tg, which is an increase of 4.4 Tg N since 1995 (Table 1). In contrast to what is observed for North America and globally, the main source of the new N inputs in Brazil is BNF in agriculture, which has more than doubled since 1995 (Table 1) especially because of the expansion of soybean cultivation (Figure 11). In 2004, the area planted with soybeans in Brazil was estimated at over 21 million ha (IBGE 2004), or about 2.7 million ha more than in 2002, that translates to an additional 0.46 Tg N in 2 years, assuming conservative rates of fixation.

We speculate that the importance of BNF in agriculture in Brazil is likely to increase in the future not only because of further expansion of soybean

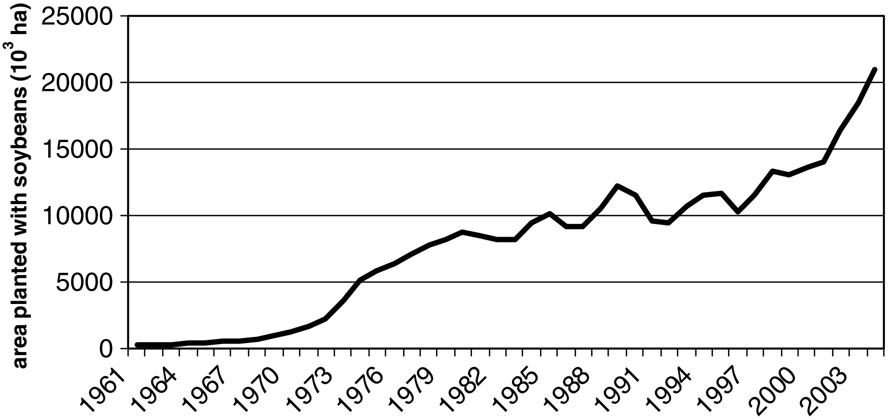


Figure 11. Area planted with soybeans in Brazil in the period between 1960 and 2003. Source: IBGE (Brazilian Institute of Geography and Statistics).

cultivation, but also because of the expansion of area planted with sugarcane for the production of ethanol, which Brazil plans to export in the next few years. Moreover, new technology and management strategies are now being developed in Brazil to improve rates of BNF in pastures (S. Urquiaga, personal communication 2004).

Besides BNF in agriculture, the use of nitrogen fertilizer in Brazil has more than doubled between 1995 and 2002 (Table 1), and is the second largest source of anthropogenic Nr in Brazil. Yet, the total amount of the fertilizer that is used presently in the country is about one-fifth of the amount used in North America, and is only a minor fraction of the global consumption (Table 1). The relatively low use of N fertilizer in Brazil is associated with high costs of the product in the country, which is mostly imported (~70%). However, as prices of fertilizer increase, roads improve, and agriculture intensifies in Brazil, the consumption of N fertilizer will tend to increase considerably, as has been the trend observed in the country over the past decade (Figure 3).

Energy production contributes a relative small amount of anthropogenic N in Brazil (Table 1) and has contributed little in the Nr budgets. However, because about 95% of the NO_x emissions in Brazil associated with energy production is related to the combustion of oil and derivatives for on-road vehicles, emissions are likely to increase with the number of vehicles increase (Figure 12).

Since the pre-industrial era, inputs of Nr from anthropogenic sources in Brazil have increased significantly but, according to our estimates for 2002, natural sources are still dominant, contributing approximately 11.4 Tg N yr^{-1} from both BNF in natural vegetation, and lightning (Table 1). The inputs from natural sources have been estimated using biological N fixation rates from the scientific literature for different types of natural vegetation in the tropics

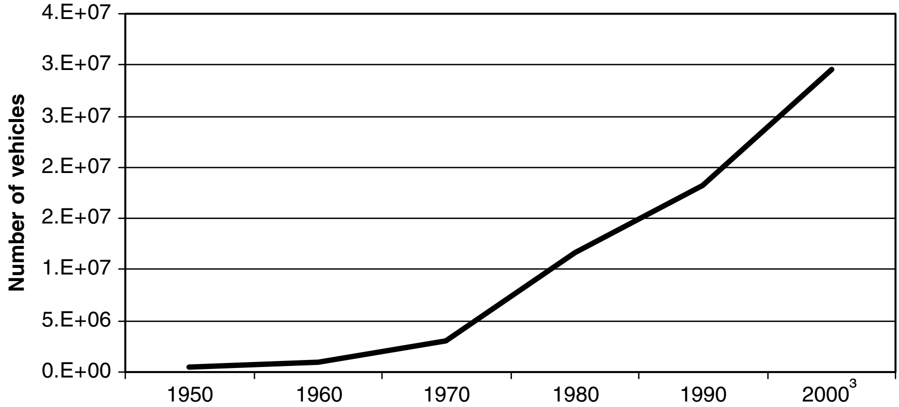


Figure 12. Number of on-road vehicles in Brazil between 1950 and 2000. Source: DENATRAN (Brazilian National Department of Transit).

(Cleveland et al. 1999) and model simulations of N deposition from lightning in South America in the early 1990s (Dentener and Crutzen 1994; Lelieveld and Dentener 2000). Therefore, these values are an approximation and should be interpreted with caution.

The values of BNF in the Amazon forest, for instance, were calculated based on the assumption that 70% of the basin soils are highly weathered *Ultisols* and *Oxisols* (Martinelli et al. 1999), and therefore should have BNF rates, based on 5% average cover of symbiotic N fixing vegetation (Cleveland et al. 1999) (Table 4). For the remaining 30% of the basin with richer soils, fixation rates were assumed to be higher and based on 15% cover of symbiotic N fixers (Cleveland et al., 1999). The other values used for estimation of BNF in different biomes of Brazil were multiplied by the estimated area of natural vegetation in each biome (Table 4).

Because much of the new anthropogenic N inputs in Brazil are associated with land use change and the expansion of agricultural area, there is a con-

Table 4. Natural N fixation rates in main Brazilian biomes based on values from Cleveland et al. (1999). Fixation rates used for 70% and 30% of the Amazon basin were 14.7 and 25.8, respectively.

Biome	N fixation rate
Amazonia (Rainforest)	14.7 or 25.4
Cerrado (Tropical savanna)	30.2
Caatinga (Xeromorphic forest)	9.4
Atlantic forest (Tropical deciduous forest)	21.6
Araucaria (Tropical evergreen forest)	15.0
Pantanal (Tropical non-forest floodplain)	28.5
Campos (Short grassland)	2.7

Values are in Kg ha^{-1} yr^{-1}.

comitant loss of natural vegetation in the country and consequent reduction of natural inputs of N from BNF. For instance, we estimated that under pristine conditions, BNF in natural vegetation contributed 17.1 Tg N yr^{-1} to the N budget in Brazil and that presently, because of a reduction in area, this contribution is approximately 11.4 Tg N yr^{-1}. Therefore, while net N inputs from anthropogenic sources increased about 9.4 Tg N yr^{-1} since the period when Brazil vegetation was pristine, there was a decrease of 5.7 Tg N yr^{-1} from natural biological fixation. Therefore, anthropogenic inputs of N in Brazil have actually increased the overall N budget by only about 3.7 Tg yr^{-1}. This is a relatively small number in comparison to the total inputs in the country, and is probably within the margin of error because the fixation rates can vary significantly depending on the assumed density of N fixers in the different biomes in Brazil (Cleveland et al. 1999) and on the fixation rates in soybeans (ranging from 70 to 250 kg ha^{-1} yr^{-1}) and pastures (averaging 15–30 kg ha^{-1} yr^{-1}). However, we can conclude that the N cycle in Brazil is increasingly controlled by anthropogenic activities and less controlled by natural processes. In different regions of Brazil, however, the importance of a natural versus an anthropogenically controlled N cycle becomes a much more prominent issue, especially because of the uneven distribution of the human population throughout the country and the intensity of agriculture in the different regions. Therefore, in order to assess this variability in Brazil, below we discuss some preliminary estimates of the major Nr sources in contrasting regions of Brazil, including the Amazon, the *Cerrado*, and the Southeast during the late 1990s and early 2000s.

Three contrasting regions in Brazil (Amazon, Cerrado and southeast)

The Amazon basin represents a relatively pristine region of Brazil and occupies close to 60% of the Brazilian territory, while the Brazilian *Cerrado* encompasses more than 20% of the country area and has vast areas of pastures and natural vegetation which are being converted to high-intensity agriculture. The Southeast region is the most developed part of Brazil and also one of the first areas to go through the process of land use changes, urbanization and industrialization.

The total area of the legal Amazon basin is over 6.3 million km^2, with about 5 million km^2 of continuous tropical forest extending to portions of eight countries, including 47.1% of the Brazilian territory. In Brazil, the Amazon basin extends for approximately 5 million ha, most of which is forested and tropical savanna landscapes, while land undergoing first stages of development (i.e., pastures and low intensity agriculture) are the second most dominant land use. The representation of more advanced stages of development in the basin, including high intensity agriculture and urbanization, is still relatively small but growing steadily in the southwestern region. Deforestation rates in the Brazilian Amazon averaged nearly 2 Mha yr^{-1} in the past 25 years

(INPE, 2000), and large-scale cattle ranches appear to be responsible for ~70% of all forest loss (Fearnside 2005). Fire is the most prevalent type of agricultural management in the region, especially for cattle ranching and slash-and-burn farming (Nepstad et al., 1999).

The *Cerrado* is an extensive phytogeographic zone located in the central portion of Brazil, covering over 200 Mha or 20% of the Brazilian territory (Ratter et al. 1997). This phytogeographic zone is located entirely within Brazil (Figure 13), extending from just south of the equator to south of the Tropic of Capricorn. Longitudinally, the *Cerrado* extends from east of the Tocantins River basin to the border of Brazil with Bolivia and Paraguay. The region includes a wide variety of vegetation types ranging from native grasslands to dense arboreal formations and dendritic forests that follow courses of water (Ratter et al. 1997). The three primary structural types of plant communities in the *Cerrado* include medium to tall woodlands with closed or semi-closed canopies (*cerradão*), savanna woodland or low trees and shrubs (*cerrado sensu stricto*), and open savanna with scattered trees or shrubs (*campo sujo*) (Pinto et al. 2002). One of the main characteristics of the *Cerrado* is that it is situated over a plateau and, therefore, it has vast areas (~127 Mha) of gentle topography suitable for mechanized agriculture. In the last 35 years, the *Cerrado* has lost over 40% of its native vegetation (Machado et al. 2004) due to the enormous advances in the agricultural frontier and the expansion of soybean plantations in the region (FAOSTAT 2004). Yet, the Brazilian Ministry of

Figure 13. Map of Brazil with the delineation of the major biomes in the country. Area shaded corresponds to the state of São Paulo. Source: WWF (http://www.wwf.org).

Agriculture estimates that Brazil's potential for agricultural expansion is about 90 million hectares (USDA 2003), and that most of the expansion is likely to occur in the *Cerrado* in the coming decades. These impacts are likely to have major ecological consequences for many of the major rivers with headwaters in the C*errado* region, such as the Paraná, São Francisco, Tocantins, and Araguaia.

Also, as in other tropical savannas, natural fires are a common feature of the *Cerrado*. Most savanna ecosystems are burned every 1–4 years during the dry season, with the highest frequency in the humid savannas (Nardoto and Bustamante 2003). Fires in the *Cerrado* have been occurring for thousands of years, but because of land use changes and agricultural management practices common in the region, they are becoming increasingly more frequent, and changing the grass/wood biomass ratio (Coutinho 1990).

The southeastern region of Brazil, here represented by the state of São Paulo because of data availability, has the most advanced stages of development in the Southern Hemisphere, with intensive agriculture, and high industry and population densities. The region also includes several dams constructed for hydroelectric power, which commonly characterizes development in the tropics (Downing et al. 1999). In terms of land use, the southeastern region is also the most diverse in terms of stages of development, especially because of the long-term history of deforestation, agriculture, and industrialization processes which started during the 17th century in São Paulo with deforestation followed by cultivation of coffee and sugar-cane (Martinelli et al. 2000).

Anthropogenic N sources in the Amazon, Cerrado and São Paulo

Our estimates show that BNF in agriculture is the largest source of anthropogenic N in all three regions (Table 5). In the Amazon, N inputs from BNF in agricultural systems are dominant mainly because of N fixation in actively grazed cattle pastures which cover an estimated area of 25 million ha (Bernoux et al. 2001; Müeller et al. 2004) and create approximately 0.75 Tg N yr^{-1} to the region. Soybean plantations, on the other hand, cover only about of 73,000 ha of the Amazon (Müeller and Bustamante 2002) and contribute to an estimated 0.01 Tg N yr^{-1} to the total budget. Inputs from BNF in actively grazed cattle pastures of the Amazon are also high because water stress is not as prevalent as

Table 5. Anthropogenic N sources in the Amazon, Cerrado and São Paulo State in Tg yr^{-1}.

	Amazon	Cerrado	S. Paulo
Lightning	0.26	0.12	0.01
BNF	7.5	1.74	0.05
Fertilizer	0.14	0.51	0.30
BNF-ag.	0.92	2.5	0.36
Atm. deposition	0.07	0.08	0.06

Table 6. Anthropogenic N sources in the Amazon, Cerrado and São Paulo State in kg km^{-2} yr^{-1}.

	Amazon	Cerrado	S. Paulo
Lightning	74	59	40
BNF	2142	853	201
Fertilizer	40	250	1210
BNF-ag.	263	1225	1452
Atm. deposition	20	39	246

in pastures of other major regions of Brazil such as the *Cerrado*. Therefore, fixation rates average about 30 kg ha^{-1} yr^{-1} (S. Urquiaga, personal communication, 2004), in contrast to 15 kg ha^{-1} yr^{-1} assumed for the other regions.

Since fixation rates in active cattle pastures of the Amazon are comparable to those of the rainforest (Table 4), the new inputs of N in the region through BNF in pasture land are not likely to affect N fluxes in the ecosystems on a large scale. However, as soybean plantations expand further into the Amazon, rates of N inputs from anthropogenic sources will far exceed natural inputs (Table 6) and potentially increase delivery rates of N to aquatic systems. This, however, will depend on whether or not N from BNF in soybeans accumulates in the soil over time. Soybeans are generally very efficient at utilizing available N in the soil before investing in N fixation (Peoples et al. 1995; Alves et al. 2003). Consequently, it is possible that soybean production in the Amazon will lead to the depletion of N from the soil rather than accumulation.

In the *Cerrado*, inputs of agricultural BNF are mostly from soybean cultivation. In 2002, the *Cerrado* had approximately 10 million ha of soybean fields, with fixation rates as high as 250 kg ha^{-1} yr^{-1} (Alves et al. 2003). Using a conservative rate of 170 kg ha^{-1} yr^{-1}, we estimated that soybeans added at least 1.7 Tg N to the *Cerrado* N budget in 2002. However, as most of this newly fixed N, and potentially some soil N, is exported from the region with harvested soybeans, the net input of N in the *Cerrado* is much lower than the gross input.

Fixation rates in *Cerrado* pastures ($\sim$15 kg ha^{-1} yr^{-1}, S. Urquiaga, personal communication, 2004) are lower than those of soybeans while the export of N from the region in cattle meat should be on the order of 9 kg ha^{-1} yr^{-1} in pastures grazed by 2–4 beef cattle ha^{-1} (Boddey et al. 2004). Therefore, well-managed pastures could potentially lead to N accumulation in the *Cerrado*, except that significant quantities of N can be lost from *Brachiaria* pastures in Brazil from animal excreta through volatilization, denitrification or leaching (Boddey et al. 2004). Losses from animal excreta increase with the number of grazing animal per hectare, and when these losses surpass the potential rates of BNF in pasture they can actually yield to a depletion of N from pastures in the *Cerrado*. In addition, given that the natural vegetation of the *Cerrado* can fix, on average, about 30 kg ha^{-1} yr^{-1} (Cleveland et al. 1999) (Table 4), the replacement of natural vegetation in the *Cerrado* with cattle ranching can lead to increasing N deficiency in the region's ecosystems.

In São Paulo state, where advanced stages of development such as urbanization, industrialization, and intensive agriculture are prevalent, estimated agricultural BNF is the largest input, but is not significantly different from inputs from fertilizer. According to our budget, these two sources combined contributed 0.66 Tg yr^{-1} or over 80% of all the inputs (Table 5), with about 0.08 Tg N yr^{-1} originating from biological fixation in 2.3 Mha of sugarcane plantations, 0.15 Tg N yr^{-1} from 10.3 Mha of cattle pastures, and 0.13 Tg N yr^{-1} from 0.74 Mha of soybeans. With a population of about 37 million people in 2000 (SIDRA/IBGE 2004) and an estimated consumption of N in food on the order of 0.15 Tg, assuming a per capita consumption of 4 kg N yr^{-1}, we predict that significant amounts of the N inputs from fertilizer and BNF in agriculture are not exported with foodstuffs from the state and are likely to be transferred to rivers and other aquatic systems with sewage discharges (Filoso et al. 2003). However, because the state of São Paulo exports much of its agricultural products to other parts of Brazil, the net input of N from anthropogenic sources in São Paulo should be considerably lower than gross inputs. Unfortunately, lack of data on imports and exports of agricultural products among the different states and territories in Brazil makes it difficult to estimate net N inputs more accurately for individual regions.

Among all of the anthropogenic N sources in the three comparison regions, atmospheric deposition was the least important (Table 5). Results from the model simulations for atmospheric N deposition in South America predicted that N inputs from the atmosphere can be significant in the overall budget of Brazil (5 to 12.5 kg ha^{-1} yr^{-1}), or in pristine regions such as the Amazon because of natural soil emissions and biomass burning. However, when emissions from fossil fuel are considered the only new source of N in the regions, the importance of atmospheric deposition inputs are reduced significantly, especially in the Amazon and *Cerrado*, where population densities average about 1 and 5 people km^{-2}, respectively (SIDRA/IBGE 2004). In São Paulo, where population density is about 150 people km^{-2}, the relative contribution of atmospheric deposition is considerably higher because fossil fuel emissions are substantial.

When comparing N inputs in the Amazon, *Cerrado* and São Paulo on a per area basis, we observe that the highest N input rates from anthropogenic sources occur in São Paulo (Table 6), probably because more than 90% of the territory in the state has been converted to agricultural or urban lands in the past few centuries. In the *Cerrado*, inputs of N from BNF in agricultural systems are about seven times higher than those in the state of São Paulo (Table 5), but rates on a per area basis are significantly lower because of the vast area of natural vegetation (~60%, IBGE 2004) that still covers the region. However, with the fast expansion of soybean cultivation in the *Cerrado*, and also with improving pasture management practices, rates of BNF in agriculture are likely to surpass those of the Southeast region of Brazil in the near future. Moreover, agriculture in the *Cerrado* is increasingly less associated with the monoculture of soybeans, and more with a diversity of crops including corn and cotton (Machado et al. 2004). Therefore, rates of N fertilizer use are also likely to grow following the trend observed for the country in general. Higher input rates of N fertilizer in the *Cerrado*, however, would have a much higher impact on the total N budget of Brazil because of the size of the region. Presently, total inputs of N from fertilizer use in the *Cerrado* are already higher than in São Paulo (Table 5), even though rates per area are lower. The same pattern is observed for inputs of N through BNF in agriculture.

Considering all the sources of N accounted for in the different regions of Brazil, the highest rates were estimated for natural BNF in the Amazon basin (Table 6), which is reflected in the total N budget for Brazil (Table 1) because of the vast area of the region. However, as land use change alters the N cycle in the Amazon, the importance of natural BNF in the overall budget will tend to decrease, while biological fixation of N is likely to remain the dominant mechanism for the creation of new N in Brazil. This is not just because of the potential expansion of soybean plantations and well managed pastures, but also because of the expansion of secondary forests in the Amazon. In tropical humid forests, BNF tends to be higher in young and secondary forest stands than in older stands in primary forests (Martinelli et al. 1999), indicating that the increasing area of secondary forests in the Amazon may be contributing to the increase of anthropogenic nitrogen inputs to the global budget (Galloway et al. 2004).

Conclusions

Although the alteration of the N cycle by human activities have been mainly associated with the temperate zone, especially Europe and the US, our evaluation of Nr inputs and outputs in Brazil presented in this paper suggests that the N cycle in developing regions of the tropics is increasingly less controlled by natural processes and more by human activities. Natural biological N fixation is still the main source of N in Brazil, but anthropogenic inputs are practically equivalent. In contrast to developed regions of the temperate zone, most of the newly created N originates from BNF in agricultural systems such as soybean crops and pastures, not from nitrogenous fertilizers or fossil fuel combustion. However, in regions of Brazil such as the southeast, which are undergoing more advanced stages of development, inputs of N from fertilizer application and combustion of fossil fuel are relatively high. In more pristine regions such as the Amazon, rates of N inputs from anthropogenic sources are still small, but the overall inputs are considerable because of the relatively large area of the region in Brazil (~40% of the overall territory). In the Brazilian *Cerrado*, which is the second largest biome of Brazil, the impact of anthropogenic activities on the N cycle is already visible on the N budget for Brazil and Latin America in general.

Except for N inputs from inorganic fertilizer, however, the estimates of N flows presented in this paper indicate general patterns and trends that are occurring to the N cycle in Brazil and regions, and should not be interpreted as absolute values. In many cases, such as the N inputs from BNF in soybeans, the real fluxes may be higher than the average estimates. In other cases, such as inputs from BNF in sugarcane, fluxes may be lower than estimated. Yet, the present study provides the first overview of the factors contributing to the changing N cycling in Brazil and other developing regions of the tropics, which should be helpful in outlining the priorities for improving our understanding of the effects of human activities on the N cycle in this part of the world. For instance, we now know that Nr inputs through BNF in cultivated pastures of the Amazon are potentially a major source of newly fixed N to the local and global budgets, so improved estimates that include field measurements of BNF rates and long-term monitoring of land use are necessary for improving the budgets. Challenges related to data availability and quality are not only unique to Brazil, and should be considered as a major priority for the advancement of our understanding of the impacts of human activities on the N cycle at the global scale.

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