

## Direct nitrous oxide (N<sub>2</sub>O) fluxes from soils under different land use in Brazil—a critical review

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## Environmental Research Letters



## TOPICAL REVIEW

Direct nitrous oxide (N<sub>2</sub>O) fluxes from soils under different land use in Brazil—a critical review

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Brazil typifies the land use changes happening in South America, where natural vegetation is continuously converted into agriculturally used lands, such as cattle pastures and croplands. Such changes in land use are always associated with changes in the soil nutrient cycles and result in altered greenhouse gas fluxes from the soil to the atmosphere. In this study, we analyzed literature values to extract patterns of direct nitrous oxide (N<sub>2</sub>O) emissions from soils of different ecosystems in Brazil. Fluxes from natural ecosystems exhibited a wide range: whereas median annual flux rates were highest in Amazonian and Atlantic rainforests (2.42 and 0.88 kg N ha<sup>-1</sup>), emissions from cerrado soils were close to zero. The decrease in emissions from pastures with increasing time after conversion was associated with pasture degradation. We found comparatively low N<sub>2</sub>O-N fluxes from croplands (−0.07 to 4.26 kg N ha<sup>-1</sup> yr<sup>-1</sup>, median 0.80 kg N ha<sup>-1</sup> yr<sup>-1</sup>) and a low response to N fertilization. Contrary to the assumptions, soil parameters, such as pH, C<sub>org</sub>, and clay content emerged as poor predictors for N<sub>2</sub>O fluxes. This could be a result of the formation of micro-aggregates, which strongly affect the hydraulic properties of the soil, and consequently define nitrification and denitrification potentials. Since data from croplands mainly derived from areas that had been under natural cerrado vegetation before, it could explain the low emissions under agriculture. Measurements must be more frequent and regionally spread in order to enable sound national estimates.

**1. Introduction**

The Food and Agriculture Organization of the United Nations (FAO 2014) has ranked Brazil as the third largest emitting country of greenhouse gases (GHG) from agriculture for the year 2012. One reason is the significant increase in area used for agriculture in recent years (Cederberg *et al* 2009). However, GHG budgeting at national scales is full of uncertainties, particularly for such large countries, and too little is known about the processes that affect such estimations. Literature reviews are one viable first step towards improvements (e.g. Jungkunst *et al* 2006), which can eventually lead to further extrapolations to the national scale (e.g. Brocks *et al* 2014). For the agricultural sector nitrous oxide (N<sub>2</sub>O) is one of the

most important GHG. It is emitted from soils by natural processes, which can be enhanced and potentially reduced by anthropogenic activities, such as fertilization and land use changes. The principle underlying prerequisite for N<sub>2</sub>O emission is the availability of nitrogen. Nitrogen in soils is increased by fertilization, which usually leads to increased N<sub>2</sub>O emissions. The Intergovernmental Panel on Climate Change (IPCC 2006) assumes this relationship between N fertilization and N<sub>2</sub>O emissions to be linear and defines an emission factor (EF) of 1% (1 kg of every 100 kg of applied N fertilizer is lost as N<sub>2</sub>O-N). At the same time, the IPCC strives to improve this approximation to more detailed region-specific approaches. Based on data from temperate climates (e.g. Boeckx and van Cleemput 2001), as well as global

scale data (Shcherbak *et al* 2014), a single emission factor is imprecise. Shcherbak *et al* (2014) rather proposed a nonlinear relationship at the global scale. These insights lead to the conclusion that the relationship between fertilizer input and N<sub>2</sub>O emissions must vary according to environmental settings like climate and soil conditions (Jungkunst *et al* 2006). Considerably less data exists for the tropics compared with temperate regions (Shcherbak 2014). However, data available from tropical areas indicate that the emission factor used by the IPCC overestimates measured fluxes (Madari *et al* 2007, Jantalia *et al* 2008, Alves *et al* 2010, Cruvinel *et al* 2011, Alvarez *et al* 2012, Carmo *et al* 2013, Carvalho *et al* 2013, Lessa *et al* 2014).

Estimations for national N<sub>2</sub>O inventories are challenging, because soils are diffusive emitters and direct N<sub>2</sub>O fluxes show extremely high temporal and spatial heterogeneities (e.g. Groffman *et al* 2009). The largest emissions of N<sub>2</sub>O mainly result from denitrification under hypoxic conditions (Davidson *et al* 2000); especially during changes between well aerated (WFPS at 40–60%) and wet (WFPS ≥ 80%) conditions (Vor *et al* 2003). Consequently, when soil moisture increases during wet seasons, N<sub>2</sub>O emissions commonly increase as well (e.g. Luizão *et al* 1989). In irrigation experiments by Vasconcelos *et al* (2004) and Carvalho *et al* (2013), N<sub>2</sub>O fluxes increased after irrigation during the dry season in Brazil.

Luizão *et al* (1989) and Sotta *et al* (2008) reported that finer textured soils have a higher N availability. Additionally, Matson *et al* (1990) and Sotta *et al* (2008) measured higher N<sub>2</sub>O losses from clay soil compared to sand soil. Since tropical soils of Brazil are commonly rich in clay and experience regular changes in moisture through seasonal rainfall patterns, Brazilian soils should emit higher amounts of N<sub>2</sub>O than temperate soils. However, reported measurements show fairly low emission levels. Stable micro-aggregates, which form due to adhesion of fine soil particles and (iron-)oxides, are known to create a coarser structure. This leads to better drainage and more oxic conditions than would be expected by measured clay contents. When compared with other predominant soils at the global scale, the general role of clay content as an indicator for N<sub>2</sub>O fluxes can be questionable.

Besides accounting for N<sub>2</sub>O emission from specific land use types, N<sub>2</sub>O dynamics during actual land use changes should be accounted for, particularly with respect to the rapid land use change happening in Brazil. The expansion of cattle ranching is suggested to be the main driver of recent deforestation in the Legal Amazon (e.g. Barona *et al* 2010). However, Morton *et al* (2006) reported an increasing trend of cropland deforestation (direct conversion of forest to cropland) between 2001 and 2004 in the state of Mato Grosso.

Tropical forests have high rates of biological turnover and decomposition. High soil moisture and N availability increase these soils emissions of N<sub>2</sub>O (Davidson *et al* 2000). Breuer *et al* (2000) estimated a

N<sub>2</sub>O budget of 3.55 Tg N<sub>2</sub>O-N yr<sup>-1</sup> from tropical rainforest soils. In contrast to rainforests, reported emissions from soils under natural cerrado vegetation (forest to treed grassland ecosystems) were usually very low (Davidson *et al* 2001) or even negative (e.g. Carvalho *et al* 2013). Consequently, knowing the natural ecosystem present before the land use change may be as important in estimating N<sub>2</sub>O emissions as knowing the current agricultural land use.

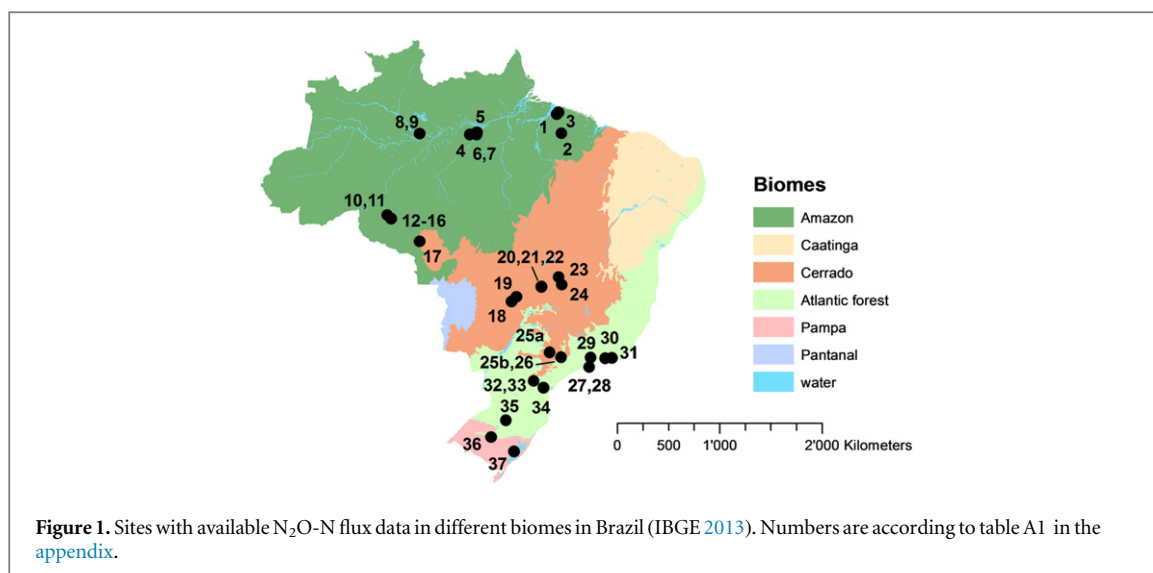
Here, we focus on the regional scale within Brazil in order to improve estimates for atmospheric N<sub>2</sub>O increase. Considering single studies without a systematic scientific compilation is neither sufficient to identify regional measurement gaps nor to identify underlying key processes. The value of understanding specific soil and management properties to indicate N<sub>2</sub>O fluxes not only lies in better approximations, but also feeds process-based models that are eventually needed for scenario calculations to derive mitigation strategies. A systematic review additionally can help to derive research strategies and to set the basis for regional and temporal N<sub>2</sub>O measurement recommendations, based on revealed relationships with environmental parameters. The improved process understanding enables better national estimations.

To provide this we used reported emissions of N<sub>2</sub>O-N from soils under different land use. Specifically, we aimed to (1) compare reported N<sub>2</sub>O-N fluxes from different land use types and define average annual emissions, (2) evaluate if specific soil and management properties can serve as an indicator of N<sub>2</sub>O fluxes, and (3) determine knowledge gaps for improvements of future national N<sub>2</sub>O inventory and process understanding.

## 2. Materials and methods

### 2.1. Data collection and calculation

We searched English literature for N<sub>2</sub>O-N flux data from soils under different land use across Brazil using online databases (Web of Science, Science Direct, Scielo (Brazilian)) and search engines (Google Scholar) between March 2014 and January 2015. Search queries initially included the keywords 'N<sub>2</sub>O' AND 'soil' AND 'Brazil', which resulted in large numbers of studies (e.g. 73 studies in the Web of Science). We further specified the search by adding the keyword 'conversion'. Additional specification of the single land use types (AND 'rainforest'/'pasture'/'cropland') or geography (AND 'Amazon'/'Southern Brazil') did not result in additional studies. According to the guidelines of Aiassa *et al* (2015) on how to proceed on systematic reviews, we made use of personal contacts and contacted research groups in Brazil (EMBRAPA) to improve and expand our search strategies towards Portuguese studies that might have been missed using the Scielo database and due to linguistic difficulties. No time frame was set in terms of the age of the studies



—the aim was to gather a good geographic coverage of Brazil. Only tabular values were analyzed; we did not extract data from graphs. Data sets were divided into three categories: (1) data from natural landscape units (Amazon forest, Atlantic forest, and cerrado), (2) land that was converted to pastures, and (3) land under agricultural management and fertilizer application. Since the third category contained long-term (one year or more), as well as short-term experiments (weeks or months), studies within this category were again divided according to the duration of the measurements. Short-term experiments usually presented as cumulative fluxes over the specific time period rather than annual emissions. Nevertheless, we treated short-term experimental data as long-term data if authors extrapolated to annual values (e.g. Metay *et al* 2007). Similarly, cumulative data resulting from different crops within a rotation (e.g. corn/bean rotation, Cruvinel *et al* 2011) were extrapolated to annual values, if the whole rotation cycle covered one year. Reported units varied among the studies, thus we converted data sets to identical units (e.g. kg N ha<sup>-1</sup> for N<sub>2</sub>O fluxes and fertilizer inputs, or g kg<sup>-1</sup> for C<sub>org</sub>). If N<sub>2</sub>O fluxes were not given in annual emissions, but mean daily values were given, reported data were projected to one year. For studies which distinguished between dry and wet seasons, the length of the specific period was used in the extrapolation. Soil types were classified according to the World Reference Base (IUSS 2014). Soil texture, usually expressed as clay content, carbon content, and pH have been shown to influence N<sub>2</sub>O-N emissions. Thus, we looked at correlations with available soil properties, as well as with the amount of applied fertilizer. The latter did not include studies including soybean because legumes are treated differently by the IPCC. Forests and cerrados were not included in the regression analysis because information on the specific soil properties were derived from the mineral soil, but not from the overlying humus layer. We differentiated between

fertilized and unfertilized plots (usually pastures and croplands). Except for correlations with the amount of applied fertilizer, we only regarded fertilizer-induced emissions (N<sub>2</sub>O-N/added N). Data from pastures were ordered according to the time since establishment, as pasture ages turned out to be a meaningful factor in forest areas converted to pastures (e.g. Wick *et al* 2005, Neill *et al* 2005).

## 2.2. Statistical analyses

We used the linear regression method to analyze the relationships between soil properties and N<sub>2</sub>O-N emissions. The influence of the applied fertilizer was additionally adapted by a nonlinear model, following the suggestions of Shcherback *et al* (2014). Relationships were regarded as being statistically significant for a *p* value of (or smaller than) 0.05. The regression analyses and creation of graphics were conducted using the R software (version 2.15.0).

## 3. Results

In total, 37 study sites were analyzed based on land use, soil properties, management, and fertilization (table A1).

The geographical locations of the sites (figure 1) divided Brazil into regional land use types: studies conducted in the northern states (e.g. Pará, Rondônia) mainly dealt with N<sub>2</sub>O-N emissions from rainforest and cattle pastures. These land use types represented the fundamental land use change (deforestation) in the Amazon region. In contrast, studies from the central and southern states focused on conversion of cerrado area to croplands and the influence of different crop rotations, management, and fertilization strategies.

Annual N<sub>2</sub>O-N emissions collected in this study (tables 1 to 3) were differentiated according to the land use type. Table 1 summarizes data from forest (Amazon and Atlantic forest), cerrado, and pasture sites. Table 2 summarizes data from experiments on cropland.

**Table 1.** Annual N<sub>2</sub>O emissions with minimum, median, and maximum value from forest, cerrado, and pasture soils (references are according to table A1).

Biome	Annual N <sub>2</sub> O emissions [kg N ha <sup>-1</sup> ]			Reference
	Min	Median	Max	
Forest	0.38	2.29	16.20	1, 2, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 27, 28, 31
Amazon Rainforest	0.38	2.42	16.20	1, 2, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14
Atlantic Rainforest	0.44	0.88	3.42	27, 28, 31
Cerrado	-0.09	0.14	1.19	2, 17, 18, 19, 23, 24
Pasture [age]				
≤10	1.32	2.52	10.16	9, 10, 12, 14
>10	-0.27	0.90	3.62	2, 10, 11, 12, 14, 18, 19, 23, 28, 29

Table 3 gives an overview of N<sub>2</sub>O-N fluxes from short-term experiments on grassland, pasture and cropland.

### 3.1. Soil under natural vegetation

In general, N<sub>2</sub>O emissions from forest soils were higher than emissions from pasture sites (e.g. Verchot *et al* 1999, Steudler *et al* 2002, Wick *et al* 2005, Carmo *et al* 2012). Reported N<sub>2</sub>O-N fluxes from forest soils were positive without exception, but varied from 0.38 up to 16.20 kg N ha<sup>-1</sup> yr<sup>-1</sup>. Rainforests (Amazonas and Atlantic rainforest) differ considerably from cerrado: the highest emission (16.20 kg N<sub>2</sub>O-N ha<sup>-1</sup> yr<sup>-1</sup>) was reported from a forest site in the Amazon, whereas the maximum emission from Atlantic forest was much lower (3.42 kg N<sub>2</sub>O-N ha<sup>-1</sup> yr<sup>-1</sup>). In contrast, emissions from cerrado sites were exceptionally low (median: 0.14 N<sub>2</sub>O-N ha<sup>-1</sup> yr<sup>-1</sup> with a maximum of 1.19 N<sub>2</sub>O-N ha<sup>-1</sup> yr<sup>-1</sup>), and often below the detection limit (<0.6 ng cm<sup>-2</sup> h<sup>-1</sup>).

Data presented in table 1 includes studies conducted in primary or moderately altered forests. Studies from Verchot *et al* (1999), Vasconcelos *et al* (2004), and Coutinho *et al* (2010) present data from secondary forests of 12, 20, and 34 years after reforestation. Here, annual N<sub>2</sub>O-N emissions amount to 0.35, 0.94, and 0.88 kg ha<sup>-1</sup>, respectively. These results are lower than the median annual emission from primary forests reported in this study and are in the range of annual emissions from pastures.

### 3.2. Pasture soil

N<sub>2</sub>O-N fluxes from pasture soils varied widely, too, but emissions from pastures younger than 10 years were significantly ( $p < 0.05$ ) higher than from older pastures (table 1, figure 2). Thus, we differentiated data from pastures of 10 years and younger from those older than 10 years. Neill *et al* (2005) modeled the behavior of annual N<sub>2</sub>O emissions from forests and pasture sites of different ages as an exponential function. When we fitted an exponential function to our data ( $y = 0.65 + 4.15 \cdot \exp(-0.10 x)$ , with  $y = \text{flux of N}_2\text{O-N [kg ha}^{-1} \text{ yr}^{-1}]$  and  $x = \text{pasture age}$ ), we found a similar decrease in N<sub>2</sub>O-N emissions with pasture age (figure 2).

For short-term experiments on pastures under additional fertilization and soil management (table 3),

highest emissions were reported from pastures under urine application and tillage management (5.87 and 2.23 kg N ha<sup>-1</sup>). These studies were not included in the nonlinear regression (figure 2).

### 3.3. Cropland soil

Highest annual emissions occurred from crop-pasture rotations (4.26 kg N ha<sup>-1</sup> yr<sup>-1</sup>) and cropland under tillage treatment (2.42 kg N ha<sup>-1</sup> yr<sup>-1</sup>). The overall median from cropland soils was 0.80 kg N ha<sup>-1</sup> (table 2).

We could use only 6 studies (15, 16, 22, 26, 34, and 36 in table A1) for calculating an emission factor (EF), because these allowed for subtraction of background emissions. Of these, only study 22 (Santos *et al* 2008) presented long-term measurements focusing on corn and bean cultivation. EFs were 0.24% for corn and 0.13% for bean. EFs from short-term experiments (table 3) ranged from 0.13 to 5.14%, with a median of 0.38%.

Except for pH ( $R^2 = 0.21$ ,  $p = 0.06$ ), correlations with N<sub>2</sub>O-N/added N were significant (figures 3(a)–(c) and table 4), but not important. Clay contents covered a range from 13 to 86%, and the linear regression implied only a slightly increasing trend for fertilized plots (0.0009) and a slightly decreasing trend (−0.003) for unfertilized plots with higher clay contents. N<sub>2</sub>O-N/added N slightly decreased with increasing pH (−0.03) or carbon content (−0.06). On unfertilized plots, emissions increased with increasing pH (0.41), but emissions decreased with increasing carbon content (−1.38).

N<sub>2</sub>O-N fluxes increased with applied N fertilizer (figure 3(d)). In their global meta-analysis, Shcherbak *et al* (2014) found that a nonlinear model better described the relationship between N<sub>2</sub>O fluxes and fertilization than a linear model. In contrast, we found that a nonlinear model of the Brazilian data did not result in a better description of the relationship between emissions and fertilization compared with a linear model ( $R^2 = 0.20^*$  for both linear and nonlinear model). Our nonlinear model ( $y = 0.93 + 1.98 \cdot x - 0.15 \cdot x^2$ , with  $y = \text{N}_2\text{O-N flux [kg ha}^{-1} \text{ yr}^{-1}]$  and  $x = \text{applied fertilizer [kg N ha}^{-1}]$ ) does not compare well with that of Shcherbak *et al* (2014) (figure 3(d)). Besides the different intercept, which is caused by reported N<sub>2</sub>O-N fluxes at low and even zero fertilization, our model has a lower slope, due to the low emissions. Table 4 shows more detailed results of the regressions.

**Table 2.** Land use, treatment, N application, and annual N<sub>2</sub>O fluxes from soils under agricultural use in Brazil. Site numbers are according to table A1.

Site no.	Land use	Treatment	Duration [days]	Applied N [kg N ha <sup>-1</sup> ]	Annual N <sub>2</sub> O [kg N ha <sup>-1</sup> ]	
3	cropland (agroforestry)	improved fallow plot	~365			
		<i>inga edulis</i>		0	0.71	
		<i>acacia mangium</i>		0	0.88	
17	cropland	control		0	0.82	
		conventional tillage:				
		rice (1 year)		7 <sup>a</sup>	0.85	
19	cropland	rice (2 years)		15	0.63	
		crop succession		92	0.57	
20	cropland	crop-pasture rotation		222	2.00	
		disc harrowing (15 cm)		~182	114	0.04 <sup>b</sup>
22	cropland	direct seeding		114	0.01 <sup>b</sup>	
		corn		365	0	0.35
25	a) cropland ( <i>plant cane</i> )	beans	~365	80	0.54	
				0	0.20	
				80	0.30	
		MF (NPK)		60		
		MF (NK) + filter cake		122		
		MF (NP) + vinasse		87		
		MF (N), + vinasse + filter cake		149		
25	b) cropland ( <i>ratoon cane</i> )	MF		120		
		MF + vinasse		142		
		7 Mg trash, MF		120		
		7 Mg trash, MF + vinasse		142		
		14 Mg trash, MF		~242	120	
		14 Mg trash, MF + vinasse		142		
		21 Mg trash, MF		120		
32	cropland	21 Mg trash, MF + vinasse	365	142	1.26	
		tillage		165	2.42	
33	pasture/cropland	no-tillage		165	1.26	
		integrated crop-livestock (corn/grazed annual-ryegrass)		365	225	4.26
35	cropland	cropland		(+excreta)		
		continuous crop (annual-ryegrass)		165	1.26	
		native vegetation		0	0.65	
		no tillage:				
		sorghum/wheat (year 1 and 2) <sup>b</sup>		365	195/253	0.65
37	cropland	corn/wheat (year 1 and 2) <sup>c</sup>		162/94	0.71	
		conventional tillage:				
		sorghum/wheat (year 1 and 2) <sup>b</sup>		365	171/253	0.71
		corn/wheat (year 1 and 2) <sup>c</sup>		141/78	0.80	
		pigeon pea + corn		367.6	1.32	
		lablab + corn		167.5	1.12	
		vetch + corn		347	144.8	0.81
black oat + corn		98.3	-0.07			
black oat + vetch/corn + cow pea		231.7	1.32			
median					0.80	

MF: Mineral fertilizer

<sup>a</sup> From Carvalho *et al* (2007).<sup>b</sup> Reported as annual emissions.<sup>c</sup> Soybean/vetch (year 1), sorghum/wheat (year 2).<sup>d</sup> Maize/wheat (year 1), soybean/vetch (year 2).

## 4. Discussion

### 4.1. Importance of land use

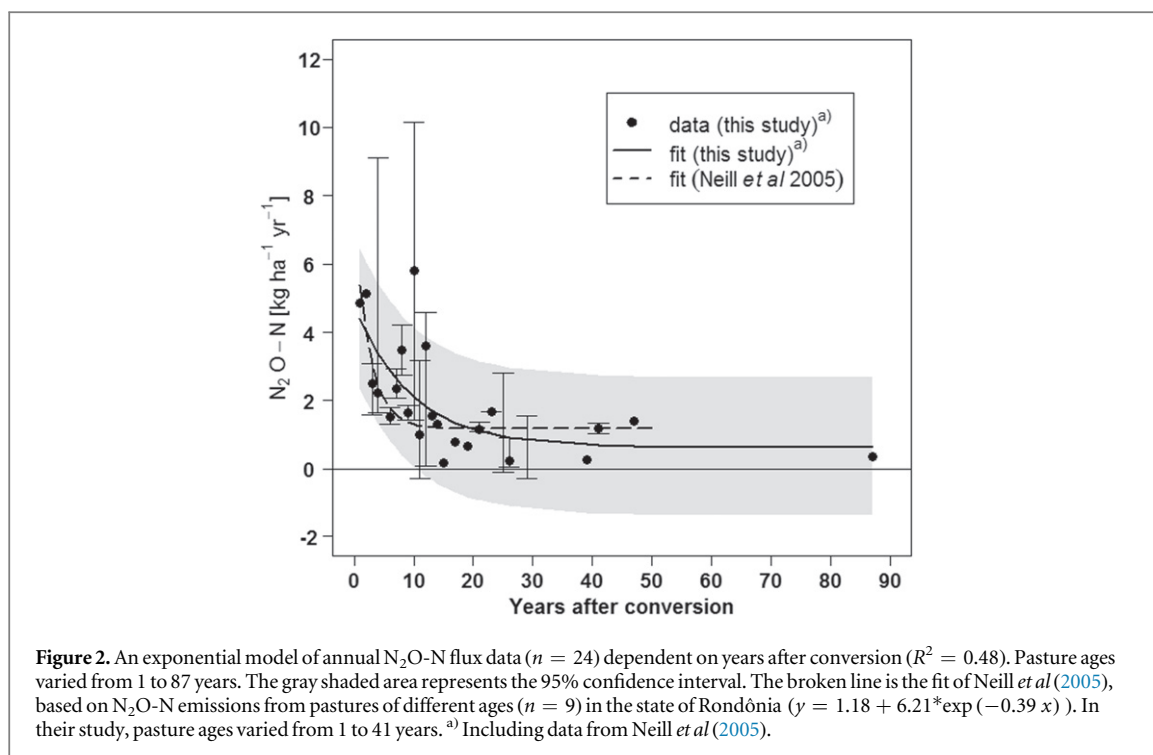
#### 4.1.1. Natural vegetation

The different emissions from cerrado and rainforest reveal the high variability of natural N<sub>2</sub>O fluxes. While emissions from Brazilian rainforest sites were

generally high (2.29 kg N<sub>2</sub>O-N ha<sup>-1</sup>), but still within the range of emissions reported for temperate (-0.1 to 4.9 N<sub>2</sub>O-N ha<sup>-1</sup> yr<sup>-1</sup>, Jungkunst *et al* 2004) and Australian tropical forests (1.15 to 5.36 N<sub>2</sub>O-N ha<sup>-1</sup> yr<sup>-1</sup>, Breuer *et al* 2000), N<sub>2</sub>O fluxes from cerrado soils were often close to zero, below detection limits (e.g. Pinto *et al* 2002, Varella *et al* 2004) or negative

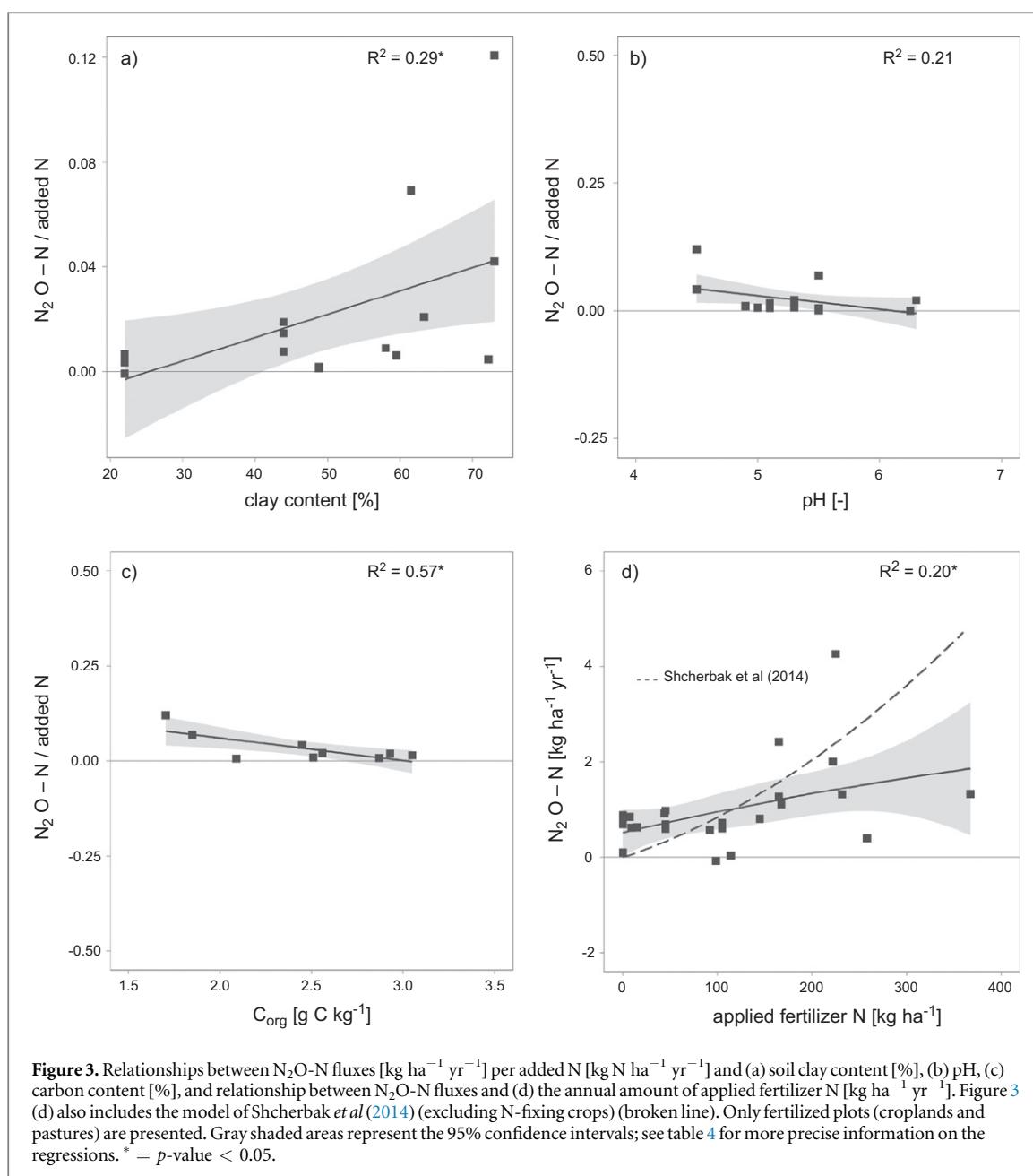
**Table 3.** Land use, treatment, N application, and cumulative N<sub>2</sub>O fluxes from soils under agricultural use in Brazil. Site numbers are according to table 5.

Site no.	Land use	Treatment	Duration [days]	Applied N [kg N ha <sup>-1</sup> ]	Cum. N <sub>2</sub> O [kg N ha <sup>-1</sup> ]
15	pasture	control		0	0.07
		tillage		42	0.23
		no-till, co-planting rice	~182	33	1.10
		no-till, co-planting soybean		0	1.10
16	pasture	control		0	0.07
		tillage	180	42	2.23
		no-tillage		33	1.62
21	pasture	urine application	94/37	396 <sup>a</sup> /683 <sup>b</sup>	
		dung application	94/37	188 <sup>a</sup> /346 <sup>b</sup>	
		corn	173	155.3	0.20
24	cropland	irrigated bean	135	102.7	0.20
		soybean	153	21.2	0.10
		cotton	258	0	0.10
26	grassland	control		0	0.02
		urine application	30	860	1.69
		vegetation cycles			
30	grassland	V1	162	80	0.44
		V2	178	100	0.57
		V3	149	80	1.47
34	pasture	control		0	0.04
		urine application	90	2200	5.87
		dung application		1110	1.43
36	cropland	fertilization with pig slurry			
		no-tillage	28	191	0.40
		conventional tillage		191	0.51

<sup>a</sup> Dry season.<sup>b</sup> Wet season.

(Verchot *et al* 1999). Nitrification is a more important source of N<sub>2</sub>O emissions in cerrado soils because of the better drainage caused by the coarse soil structure

(Pinto *et al* 2002). Consequently, these soils become increasingly important in terms of nitric oxide (NO) emissions. Pinto *et al* (2002) assumed low nitrification



**Table 4.** Intercepts and slopes (including the lower and upper values of 95% confidence interval) for linear regression between soil properties and  $\text{N}_2\text{O-N}$ /added N ratio for fertilized and unfertilized plots, and applied N and  $\text{N}_2\text{O-N}$  fluxes for the linear and nonlinear regression. \* =  $p$ -value < 0.05.

Regression parameter	Clay content		pH		$C_{\text{org}}$		Applied N	
	fertilized	unfertilized	fertilized	unfertilized	fertilized	unfertilized	linear	nonlinear
intercept	-0.22	1.68	0.16	-1.29	0.18	3.84	0.544	0.93
slope	0.000 09*	-0.003	-0.03	0.41*	-0.06*	-1.38	0.004	1.98*
lower	0.0002	-0.017	-0.06	0.07	-0.10	-9.04	0.0009	0.43
upper	0.0016	0.010	0.002	0.74	-0.02	6.28	0.0068	3.54
slope								-0.15
lower								-1.71
upper								1.41
$R^2$	0.29*	0.007	0.21	0.51*	0.57*	0.23	0.20*	0.20*

rates and low  $\text{NO}_3^-$  contents resulted in low  $\text{N}_2\text{O}$  fluxes. However, further attention should be paid to cerrado soils, in order to identify the underlying processes.

The Amazonian forest soils in the north of Brazil showed higher emissions than those of the coastal Atlantic forests in the south-east of the country. Only 3



studies dealt with the Atlantic forest, but 13 were found for the Amazonian rainforest. More studies from the Atlantic forest would help to confirm this difference between the two forest types. Emissions from secondary forests (12, 20, and 34 years after reforestation) ranged between 0.35 and 0.94 kg N<sub>2</sub>O-N ha<sup>-1</sup> yr<sup>-1</sup> and were lower than from primary forests. This suggests that N cycles in these reforested areas had not completely recovered. Regardless of the high emissions from rainforest soils compared with soils under other land use, precise knowledge concerning emissions during the conversion from rainforest to pasture is missing. This is a key aspect, since some studies report increased N<sub>2</sub>O emissions from soil after conversion of forest to pasture (Keller *et al* 1993, Veldkamp *et al* 1999, Davidson *et al* 2001, Melillo *et al* 2001). They explain this event with a temporal increase of N availability. The removal of plants as a sink for nutrients causes very high nutrient availability in soils (Bormann and Likens 1979), which is known to increase N<sub>2</sub>O emissions at barren sites (Repo *et al* 2009). In addition to the emissions from soil to atmosphere, soil–water degassing can be an important source for N<sub>2</sub>O fluxes directly after forest clear-cutting (Bowden and Bormann 1986).

#### 4.1.2. Pastures

According to Keller and Reiners (1994) and Melillo *et al* (2001), young pastures have increased emissions directly after a clear-cut, followed by decreasing emissions as the pastures age. Decreasing denitrification rates (N<sub>2</sub>O + N<sub>2</sub>) in mid-successional sites compared with primary forest and early successional sites may explain this trend (Robertson and Tiedje 1988).

The duration of higher N<sub>2</sub>O emissions after the creation of a pasture varies from 3 months (Elligson *et al* 2000), to over 2 years (Melillo *et al* 2001), to up to 10 years (Keller *et al* 1993). In our review, we found that N<sub>2</sub>O emissions from young pastures (≤10 years) were significantly higher than from older pastures. According to Davidson *et al* (2001), *Brachiaria spp.* grasses, which were introduced from Africa (Boddey *et al* 2004) and are commonly used for pastures in Amazonia, can be effective sinks for soil N. Quick immobilization of nitrogen that is released after the disturbance of the soil might delay the degradation of the pasture. Subbarao *et al* (2009) found a reduction in N<sub>2</sub>O emissions of more than 90% under plots with *Brachiaria* species compared with soybean plots. The *Brachiaria* roots produce and deliver nitrification inhibitors to soil-nitrifier sites (Subbarao *et al* 2009). In grazed *Brachiaria* pastures, intense uptake of nitrogen by grazing animals degrades pastures (Boddey *et al* 2004). The decrease of available N in the litter leads to a reduction in the amount of N available for plant growth. Cerri *et al* (2005) and Hohnwald *et al* (2006) also report that many pastures suffer from degradation (declining fertility and grass productivity, and increasing weed cover) already 4 to 10 years after

establishment. Thus, pastures are unsustainable—a point supported by our finding of decreasing N<sub>2</sub>O fluxes from pastures about 10 years after conversion.

#### 4.1.3. Croplands

Except for one study (site no. 3), data from croplands were derived from areas that had been under cerrado vegetation before. This might justify the low emissions from cropland, since cerrado soils appear to be a less considerable source for N<sub>2</sub>O fluxes. Although N fertilization increased emissions for short periods of 3 to 7 days after application, the reaction of the soil to N addition at the annual scale was very low. For application rates below 100 kg N ha<sup>-1</sup>, which are frequently applied, the reaction was negligible. The data collected in this study did not fully agree with the global nonlinear model suggested by Shcherbak *et al* (2014). Their model includes data from 84 locations worldwide, and is consequently designed for a much larger scale than our country-specific analysis. This difference emphasizes that large scale or global relationships may be inappropriate to apply to more regional aspects.

Annual fluxes of N<sub>2</sub>O-N from cropland soils in Brazil ranged from −0.07 to 4.26 kg N ha<sup>-1</sup>, with a median of 0.80 kg N ha<sup>-1</sup> (table 2). This value is much lower than emissions reported by Roelandt *et al* (2005) from croplands in Canada (2.27 kg N<sub>2</sub>O-N ha<sup>-1</sup> yr<sup>-1</sup>), Europe (2.47 kg N<sub>2</sub>O-N ha<sup>-1</sup> yr<sup>-1</sup>), and the United States (3.35 kg N<sub>2</sub>O-N ha<sup>-1</sup> yr<sup>-1</sup>). Highest emissions (figure 3(d)) occurred from the two cropland areas that were under either conventional tillage (2.42 kg N<sub>2</sub>O-N ha<sup>-1</sup> yr<sup>-1</sup>; Piva *et al* 2012) or integrated cropping systems (4.26 kg N<sub>2</sub>O-N ha<sup>-1</sup> yr<sup>-1</sup>; Piva *et al* 2014).

## 4.2. Importance of soils

### 4.2.1. Soil texture and structure

Soil texture and structure are highly relevant driving factors for N<sub>2</sub>O emissions, mainly as controllers of water balances and nutrient availability. Generally, finer textured soils have a higher N availability (Luizão *et al* 1989) and consequently emit higher amounts of N<sub>2</sub>O than sandy soils (Matson *et al* 1990). In a laboratory experiment, N losses from heavily weathered tropical soils were higher in a clay textured soil variation than from a sandy variation (Sotta *et al* 2008). Based on these findings Sotta *et al* (2008) suggest a higher N availability in a clay compared with a sand soil in Amazonian forests. Due to the good drainage of sandy soils, anaerobic conditions are rare and the potential for denitrification is low. In this study, clay proved to be a poor predictor for N<sub>2</sub>O emissions from fertilized (slope = 0.0009) and unfertilized plots (slope = −0.003), most likely due to the formation of micro-aggregates and the associated different water retention properties. Tomasella *et al* (2000) mention the rapid decrease in water content between saturation and −100 kPa, and underline that

Brazilian soils behave more like coarse-textured soils. As a result, the water holding capacity does not necessarily increase with increasing clay content, and nitrification is more likely to occur than denitrification. Therefore, tropical soils with high clay contents, formation of micro-aggregates, and high drainage can be expected to emit less  $N_2O$  than is reported for temperate soils. Thus, the clay content is not necessarily a reliable indicator for  $N_2O$ -N emissions from Brazilian soils.

#### 4.2.2. Soil chemical properties

In this study, neither pH nor  $C_{org}$  content seemed to have an influence on  $N_2O$ -N fluxes. However, fertilized and unfertilized plots differed. On fertilized plots, linear regression slopes were negative for both pH ( $-0.03$ ) and  $C_{org}$  content ( $-0.06$ ). For unfertilized plots, pH (slope =  $0.41$ ) turned out to be more predictive than  $C_{org}$  (slope =  $-1.38$ ). Although both parameters have been reported to influence denitrification rates (Knowles 1982), the general findings within this study suggest that  $N_2O$  fluxes occur from nitrification. Thus, pH and  $C_{org}$  are of secondary importance. The contribution of pH and especially  $C_{org}$  in the formation of micro-aggregates, however, should be further investigated.

#### 4.3. Knowledge gaps

Considerable data gaps exist for certain biomes. We found no reported  $N_2O$  emissions from the Caatinga and Pantanal biomes. Except for one site, data from croplands were derived from areas that had been established in cerrado areas, which were found to have extremely low emitting soils under natural vegetation. This lack of data hinders our ability to explain the low emissions from croplands, even after fertilizer application, and points out the need for measurements from additional land use types.

Since  $N_2O$  emissions exhibit short-termed emission peaks caused by environmental changes, high temporally resolved measurements are needed in order to explain mechanisms. Automated measurements enable continuous data acquisition, but the establishment of such studies is restricted to sites with a power supply and, for certain approaches, flat topography. Therefore, to achieve an adequate spatial measurement distribution across a large nation such as Brazil, we still have to rely on manual measurements that also take into consideration environmental (dry/wet cycles) and human induced (land conversion) changes. Biweekly measurements throughout the year, as done by most authors, are no longer suitable for increasing our understanding of biogeochemical processes. Furthermore, exact knowledge of how  $N_2O$ -N emissions change during land conversion is missing and desperately needed, since this time frame may likely account for large emission pulses that need to be accounted for in national budgeting.

Improving the existing understanding of the underlying processes, especially during land conversion can only be ensured by consistent monitoring and frequent measurements. Such monitoring data could provide the basis for further model refinement and allow for spatial and temporal extrapolations. The goal would be to develop regional solutions to improve national inventories. At this point, most process-oriented models have been developed for temperate conditions and application to tropical conditions is challenging. The different hydraulic conditions caused by micro-aggregates need to be considered, since adequate description of the soil moisture is a prerequisite for modelling  $N_2O$ -N fluxes from soils.

## 5. Conclusions

This systematic review on  $N_2O$  fluxes from Brazilian soils provides a good basis for further estimations and inventories on the national scale and eventually for explaining atmospheric  $N_2O$  increases. The land use types differed in direct  $N_2O$  fluxes from soils, but emissions were generally low. Systematic regional measurement gaps were identified, of which the Caatinga biome in northeastern Brazil is the most prominent example. Furthermore, land use types were not randomly distributed between biomes. In other words, pastures were studied in rainforest biomes, and croplands in cerrado biomes. Therefore, no predictions can be made on the behavior of  $N_2O$  fluxes from croplands in the rainforest biome. Soil parameters, such as pH,  $C_{org}$ , and clay content, had proven to be unsuitable as indicators for  $N_2O$  fluxes. Oddly enough,  $N_2O$  itself was found to be an indicator for the degradation stage of pastures, as emission levels decrease along with the productivity and years since conversion. A kind of tipping point from high to low  $N_2O$  emissions was found to be in the range of 10–15 years after forest conversion.  $N_2O$  is known to have high event-based emissions, which the current measurement concept did not account for. Future studies must focus on high temporal resolutions in order to promote process understanding. Otherwise, sound national inventories will not be possible.

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## Appendix

**Table A1.** Geographical location, climatic condition, soil type and properties of studies with N<sub>2</sub>O-N flux measurements in Brazil.

Site no.	Reference	Geographical location [°]		MAT [°C]	MAP [mm]	Soil type WRB	Clay content [%]	C <sub>org</sub> [g kg <sup>-1</sup> ]
		south	west					
1	Vasconcelos <i>et al</i> (2004)	1.31	47.95	25.5	2539	Ferralsol	20	2.20
2	Verchot <i>et al</i> (1999)	2.98	47.51		1850	Ferralsol		2.47–3.02
3	Verchot <i>et al</i> (2008)	1.11	47.78	26	2500	Leptosol		
4	Keller <i>et al</i> (2005)	3.03	54.95	25	2000	Ferralsol	80	2.50
						Acrisol	38	
5	Davidson <i>et al</i> (2004)	2.88	54.95		2000	Ferralsol	60–80	
6	Silver <i>et al</i> (2005)	2.64	54.59	25	2000	Ferralsol	60	
						Acrisol	18	
7	Varner <i>et al</i> (2003)	2.64	54.59	25	2000	Ferralsol	80	
						Acrisol	38	
8	Livingston <i>et al</i> (1988)	3.0	60.0	26	1770	Ferralsol		
						Acrisol		
9	Luizão <i>et al</i> (1989)	3.0	60.0		2200	Ferralsol		
10	Melillo <i>et al</i> (2001)	10.16	62.81	25.6	2200	Acrisol	19–29	
11	Stuedler <i>et al</i> (2002)	10.16	62.81	25.5	2200	Nitisol	23–29	
12	Garcia-Montiel <i>et al</i> (2001)	10.5	62.5	18.8–25.6	2270	Acrisol	<30	
13	Garcia-Montiel <i>et al</i> (2003)	10.5	62.5	18.8–25.6	2270	Acrisol	20–30	
14	Neill <i>et al</i> (2005)	10.5	62.5	25.6	2200	Acrisol	13–76	
15	Carmo <i>et al</i> (2005)	10.5	62.5		2270	Ferralsol		
16	Passianoto <i>et al</i> (2003)	10.5	62.5	25.5	2200	Acrisol		
17	Carvalho <i>et al</i> (2009)	12.48	60.0	23.1	2170	Ferralsol	73	1.71–2.77
18	Neto <i>et al</i> (2011)	17.78	51.91	23.3	1550	Ferralsol	54–68	1.85–2.90
19	Carvalho <i>et al</i> (2014)	17.36	51.48	23	1500–1800	Ferralsol	56–60	2.09–2.89
20	Metay <i>et al</i> (2007)	16.48	49.28	22.5	1500	Ferralsol	40	
21	Lessa <i>et al</i> (2014)	16.48	49.28			Ferralsol	43	
22	Santos <i>et al</i> (2008)	16.48	49.28	22.5	1460	Ferralsol		
23	Varella <i>et al</i> (2004)	15.65	47.75		1500	Ferralsol	57–74	2.41 4.74
24	Cruvinel <i>et al</i> (2011)	16.3	47.5			Ferralsol	49–72	
		16.25	47.61			Ferralsol	68–76	
25a								
25b	Carmo <i>et al</i> (2013)	22.25	48.56	21	1390	Lixisol	11	
		22.68	48.55			Ferralsol	29	
26	Barneze <i>et al</i> (2014)	22.7	47.61			Nitisol		3.03
27	Neto <i>et al</i> (2011)	23.56	45.08		3050		35	4.59–9.15
		23.4	45.18		2300		21	
28	Carmo <i>et al</i> (2012)	23.31	45.08	19.1–25.5	2500	Acrisol	23	
		23.4	45.25					
29	Coutinho <i>et al</i> (2010)	22.73	44.95	20	1500	Ferralsol	30–36	
30	Morais <i>et al</i> (2013)	22.76	43.68	24	1300	Acrisol	45	
31	Maddock <i>et al</i> (2001)	22.75 <sup>a</sup>	43.08 <sup>a</sup>	21	1500–2250	Ferralsol	27–29	2.01 2.03
32	Piva <i>et al</i> (2012)	24.78	49.95		1400	Ferralsol	44	2.87 3.05
33	Piva <i>et al</i> (2014)	24.78	49.95		1400	Ferralsol	44	2.87 2.93
34	Sordi <i>et al</i> (2014)	25.38	49.11		1400	Cambisol	44	2.50
35	Jantalia <i>et al</i> (2008)	28.25	52.4		1430	Ferralsol	63	
36	Giacomini <i>et al</i> (2006)	29.75	53.7			Luvisol		
37	Gomes <i>et al</i> (2009)	30.1	51.7	19.4	1440	Acrisol	22	

MAT: mean annual temperature.

MAP: mean annual precipitation.

<sup>a</sup> Coordinates from MMA/IBAMA (2006).

## References

- Aiassa E et al 2015 Applicability and feasibility of systematic review for performing evidence-based risk assessment in food and feed safety *Crit. Rev. Food Sci. Nutr.* **55** 1026–34
- Alvarez C, Constantini A, Alvarez C R, Alves B J R, Jantalia C P, Martellotto E E and Urquiaga S 2012 Soil nitrous oxide emissions under different management practices in the semiarid region of the Argentinian Pampas *Nutr. Cycl. Agroecosys.* **94** 209–20
- Alves B J R, Jantalia C P, Madari B E, Machado P L O A, Franchini J C, Santos J C, Boddey R M and Urquiaga S 2010 Emissões de óxido nitroso de solos pelo uso de fertilizantes nitrogenados em áreas agrícolas *Comunicado técnico* vol 126 (Seropédica: Embrapa Agrobiologia) p 6
- Barneze A S, Mazzetto A M, Zani C F, Misselbrook T and Cerri C C 2014 Nitrous oxide emissions from soil due to urine deposition by grazing cattle in Brazil *Atmos. Environ.* **92** 394–7
- Barona E, Ramankutty N, Hyman G and Coomes O T 2010 The role of pasture and soybean in deforestation of the Brazilian Amazon *Environ. Res. Lett.* **5** 024022
- Boddey R M, Macedo R, Tarré R M, Ferreira E, Oliveira O C P, Rezende C, Cantarutti R B, Pereira J M, Alves B J R and Urquiaga S 2004 Nitrogen cycling in Brachiaria pastures: the key to understanding the process of pasture decline *Agr. Ecosyst. Environ.* **103** 389–403
- Boeckx P and van Cleemput A 2001 Estimates of N<sub>2</sub>O and CH<sub>4</sub> fluxes from agricultural lands in various regions of Europe *Nutr. Cycl. Agroecosys.* **60** 35–47
- Bormann F H and Likens G E 1979 *Pattern and Process in a Forested Ecosystem* (New York: Springer) pp 253
- Bowden W B and Bormann F H 1986 Transport and loss of nitrous oxide in soil water after forest clear-cutting *Science* **233** 867–9
- Breuer L, Papen H and Butterbach-Bahl K 2000 N<sub>2</sub>O emission from tropical forest soils of Australia *JGR* **105** 353–26
- Brocks S, Jungkunst H F and Bareth G 2014 A regionally disaggregated inventory of nitrous oxide emissions from agricultural soils in Germany—A GIS-based empirical approach *Erdkunde* **68** 125–44
- Carmo J B et al 2013 Infield greenhouse gas emissions from sugarcane soils in Brazil: effects from synthetic and organic fertilizer application and crop trash accumulation *Global Change Biol. Bioenergy* **5** 267–80
- Carmo J B, Neill C, Garcia-Montiel D C, Piccolo M D, Cerri C C, Steudler P A, Andrade C A, Passianoto C C, Feigl B J and Melillo J M 2005 Nitrogen dynamics during till and no-till pasture restoration sequences in Rondônia, Brazil *Nutr. Cycl. Agroecosys.* **71** 213–25
- Carmo J B D, de Sousa N E R, Duarte-Neto P J, Ometto J P, Ometto J P H B and Martinello L A 2012 Conversion of the coastal Atlantic forest to pasture: chronosequences for the nitrogen cycle and soil greenhouse gas emissions *Agr. Ecosyst. Environ.* **148** 37–43
- Carvalho J L N, Cerri C E P, Cerri C C, Feigl B J, Piccolo M C, Godinho V P and Herpin U 2007 Changes of chemical properties in an oxisol after clearing of native Cerrado vegetation for agricultural use in Vilhena, Rondônia State, Brazil *Soil Till. Res.* **96** 95–102
- Carvalho J L N, Raucci G S, Frazao L A, Cerri C E P, Bernoux M and Cerri C C 2014 Crop-pasture rotation: a strategy to reduce soil greenhouse gas emissions in the Brazilian Cerrado *Agr. Ecosyst. Environ.* **183** 167–175
- Cederberg C, Meyer D and Flysjö A 2009 Life cycle inventory of greenhouse gas emissions and use of land and energy in Brazilian beef production *SIK Report* No 72
- Cerri C C, Melillo J M, Feigl B J, Piccolo M C, Neill C, Steudler P A, Carvalho M S, Godinho V P, Cerri C E and Bernoux M 2005 Recent history of the agriculture of the Brazilian Amazon Basin *Outlook Agr.* **34** 2015–223
- Coutinho R P, Urquiaga S, Boddey R M, Alves B J R, Torres A Q A and Jantalia C P 2010 Estoque de carbono e nitrogênio e emissão de N<sub>2</sub>O em diferentes usos na Mata Atlântica *Pesq. Agropec. Bras.* **45** 195–203
- Cruvinel E B F, Bustamante M M C, Kozovitsc A R and Zepp A R 2011 Soil emissions of NO, N<sub>2</sub>O and CO<sub>2</sub> from croplands in the savanna region of central Brazil *Agr. Ecosyst. Environ.* **144** 29–40
- Davidson E A, Bustamante M M C and de Siqueira Pinto A 2001 Emissions of nitrous oxide and nitric oxide from soils of native and exotic ecosystems of the Amazon and Cerrado regions of Brazil *Optimizing Nitrogen Management in Food and Energy Production and Environmental Protection: Proc. 2nd International Nitrogen Conference on Science and Policy. The Scientific World* **1** 312–9
- Davidson E A, Ishida F Y and Nepstadt D C 2004 Effects of an experimental drought on soil emissions of carbon dioxide, methane, nitrous oxide, and nitric oxide in a moist tropical forest *Global Change Biol.* **10** 718–30
- Davidson E A, Keller M, Erickson H E, Verchot L V and Veldkamp E 2000 Testing a conceptual model of soil emissions of nitrous and nitric oxides *Bioscience* **50** 667–80
- de Siqueira Pinto A, Bustamante M M C, Kisselle K, Burke R, Zepp R, Viana L T, Varella R F and Molina M 2002 Soil emissions of N<sub>2</sub>O, NO and CO<sub>2</sub> in Brazilian Savannas: effects of vegetation type, seasonality, and prescribed fires *J. Geophys. Res.* **107** 8089–95
- Elligson L J, Kauffman J B, Cummings D L, Sanford R L Jr and Jaramillo V J 2000 Soil N dynamics associated with deforestation, biomass burning and pasture conversion in a Mexican tropical dry forest *Forest Ecology and Management* **137** 41–51
- Food and Agriculture Organization of the United Nations (FAO) 2014 FAOSTAT. Rome. Obtained by World Resources Institute, CAIT Climate Data Explorer 2015 Washington, DC, (<http://cait.wri.org>)
- Garcia-Montiel D C, Steudler P A, Piccolo M, Melillo J M, Neill C and Cerri C C 2001 Controls on soil nitrogen oxide emissions from forest and pastures in the Brazilian Amazon *Global Biogeochem. Cy.* **15** 1021–30
- Garcia-Montiel D C, Steudler P A, Piccolo M, Neill C, Melillo J and Cerri C C 2003 Nitrogen oxide emissions following wetting of dry soils in forest and pastures in Rondônia, Brazil *Biogeochemistry* **64** 319–36
- Giacomini S J, Jantalia C P, Aita C, Urquiaga S S and Alves B J R 2006 Nitrous oxide emissions following pig slurry application in soil under no-tillage system *Pesq. Agropec. Bras.* **41** 1653–61
- Gomes J, Bayer C, Costa F, Piccolo M, Zanatta J A, Vieira F C B and Six J 2009 Soil nitrous oxide emissions in long-term cover crops-based rotations under subtropical climate *Soil Till. Res.* **106** 36–44
- Groffman P M, Butterbach-Bahl K, Fulweiler R W, Gold A J, Morse J L, Stander E K, Tague C, Tonitto C and Vidon P 2009 Challenges to incorporating spatially and temporally explicit phenomena (hotspots and hot moments) in denitrification models *Biogeochemistry* **93** 49–77
- Hohnwald S, Rischkowsky B, Camarao A P, Schultze-Kraft R, Rodrigues Filho J A and King J M 2006 Integrating cattle into the slash-and-burn cycle on smallholdings in the Eastern Amazon, using grass-capoeira or grass-legume pastures *Agr. Ecosyst. Environ.* **117** 266–76
- IBGE 2013 *Instituto Brasileiro de Geografia e Estatística* ([ftp://geofp.ibge.gov.br/mapas\\_tematicos/mapas\\_murais/shapes/](ftp://geofp.ibge.gov.br/mapas_tematicos/mapas_murais/shapes/))
- IPCC 2006 2006 *IPCC Guidelines for National Greenhouse Gas Inventories, Programme* Prepared by the National Greenhouse Gas Inventories Programme, ed H S Eggleston, L Buendia, K Miwa, T Ngara and K Tanabe (Japan: IGES)
- IUSS World Reference Base 2014 World reference base for soil resources 2014. International soil classification system for naming and creating legends for soil maps *World Soil Resources Reports* No 106, FAO, Rome, Italy
- Jantalia C P, Santos H P, Urquiaga S, Boddey R M and Alves B J R 2008 Fluxes of nitrous oxide from soil under different crop

- rotations and tillage systems in the South of Brazil *Nutr. Cycl. Agroecosys.* **82** 161–73
- Jungkunst H F, Fiedler S and Stahr K 2004 N<sub>2</sub>O emissions of a mature Norway spruce (*Picea abies*) stand in the Black Forest (southwest Germany) as differentiated by the soil pattern *Geophys. Res.* **109** D07302
- Jungkunst H F, Freibauer A, Neufeldt H and Bareth G 2006 Nitrous oxide emissions from agricultural land use in Germany—a synthesis of available annual field data *J. Plant Nutr. Soil Sci.* **169** 341–51
- Keller M and Reiners W A 1994 Soil-atmosphere exchange of nitrous oxide, nitric oxide, and methane under secondary succession of pasture to forest in the Atlantic lowlands of Costa Rica *Global Biogeochem. Cy.* **8** 399–409
- Keller M, Varner R, Dias J D, Silva H, Crill P, Oliviera R C Jr and Asner G P 2005 Soil-atmosphere exchange of nitrous oxide, nitric oxide, methane, and carbon dioxide in logged and undisturbed forest in the Tapajos National Forest, Brazil *Earth Interaction* **9** 1–28
- Keller M, Veldkamp E, Weitz A M and Reiners W A 1993 Effect of pasture age on soil trace-gas emissions from a deforested area of Costa Rica *Nature* **365** 244–6
- Knowles R 1982 Denitrification *Microbiol. Rev.* **46** 43–70
- Lessa A C R, Madari B E, Paredes D S, Boddey R M, Uriquiaga S, Jantalia C P and Alves B J R 2014 Bovine urine and dung deposited on Brazilian savannah pastures contribute differently to direct and indirect soil nitrous oxide emissions *Agr. Ecosyst. Environ.* **190** 104–11
- Livingston G P, Vitousek P M and Matson P Q 1988 Nitrous oxide flux and nitrogen transformations across a landscape gradient in Amazonia *J. Geophys. Res.* **93** 1593–9
- Luizão F, Matson P, Livingston G, Luizão R and Vitousek P 1989 Nitrous oxide flux following tropical land clearing *Global Biogeochem. Cy.* **3** 281–5
- de Melo Carvalho M T, Madari B E, de Oliveira Leal W G, Costa A R, de Almeida Machado P L O, Silveira P M, Moreira J A A and Heinemann A B 2013 Nitrogen fluxes from irrigated common-bean as affected by mulching and mineral fertilization *Pesq. Agropec. Bras.* **48** 478–86
- Madari B E, Costa A R, Jantalia C P, Machado P L O, Cunha M B, Martins D R, Santos J H G and Alves B J R 2007 Fator de emissão de óxido nítrico (N<sub>2</sub>O) para a fertilização com N na cultura do feijoeiro comum irrigado no Cerrado *Comunicado Técnico* vol 144 (Santo Antônio de Goiás: Embrapa Arroz e Feijão)
- Maddock J E L, Santos M B P and Prata K R 2001 Nitrous oxide emission from soil of the Mata Atlântica, Rio de Janeiro State, Brazil *J. Geophys. Res.* **106** 055–60
- Matson P A, Vitousek P M, Livingston G P and Swanberg N A 1990 Sources of variation in nitrous oxide flux from Amazonian ecosystems *J. Geophys. Res.* **95** 6789–98
- Melillo J M, Steudler P A, Feigl B J, Neill C, Garcia D, Piccolo M C, Cerri C C and Tian H 2001 Nitrous oxide emissions from forests and pastures of various ages in the Brazilian Amazon *J. Geophys. Res.* **106** 179–88
- Metay A, Oliver R, Scopel E, Douzet J M, Moreira J A A, Maraúy F, Feigl B J and Feller C 2007 N<sub>2</sub>O and CH<sub>4</sub> emissions from soils under conventional and no-till management practices in Goiânia (Cerrados, Brazil) *Geoderma* **141** 78–88
- MMA/IBAMA—Instituto Brasileiro do meio ambiente e dos recursos naturais renováveis 2006 *Reserva Biológica do Tinguá—RJ. Plano de Manejo*. (Brasília: Créditos técnicos e institucionais) p 951
- Morais R F, Boddey R M, Urquiaga S, Jantalia C P and Alves B J R 2013 Ammonia volatilization and nitrous oxide emissions during soil preparation and N fertilization of elephant grass (*Pennisetum purpureum* Schum.) *Soil Biol. Biochem.* **64** 80–8
- Morton D C, DeFries R S, Shimabukuro Y E, Anderson L O, Arai E, del Bon Espirito-Santo F, Freitas R and Morissette J 2006 Cropland expansion changes deforestation dynamics in the southern Brazilian Amazon *Proc. Natl Acad. Sci. USA* **103** 14637–41
- Neill C, Steudler P A, Garcia-Montiel D C, Melillo J M, Feigl B J, Piccolo M C and Cerri C C 2005 Rates and controls of nitrous oxide and nitric oxide emissions following conversion of forest to pasture in Rondônia *Nutr. Cycl. Agroecosys.* **71** 1–15
- Neto E S et al 2011 Soil-atmosphere exchange of nitrous oxide, methane and carbon dioxide in a gradient of elevation in the coastal Brazilian Atlantic forest *Biogeosciences* **8** 733–42
- Neto M S, de Cassia Piccolo M, Costa C Jr, Cerri C C and Bernoux M 2011 Emissao de gases do efeito estufa em diferentes usos da terra no bioma cerrado. Divisao 2—Processos e propriedades do solo. 2.1—Biologia do solo *R. Bras. Ci. Solo* **35** 43–76
- Passianoto C C, Ahrens T, Feigl B J, Steudler P A, Carmo J B do and Melillo J M 2003 Emissions of CO<sub>2</sub>, N<sub>2</sub>O, and NO in conventional and no-till management practices in Rondônia, Brazil *Biol. Fertil. Soils* **38** 200–8
- Piva J T, Dieckow J, Bayer C, Zanatta J A, Moraes A, Pauletti V, Tomazim M and Pergher M 2012 No-till reduces global warming potential in a subtropical Ferralsol *Plant Soil* **361** 359–73
- Piva J T, Dieckow J, Bayer C, Zanatta J A, Moraes de A, Tomazi M, Pauletti V, Barth G and de Cassia Piccolo M 2014 Soil gaseous N<sub>2</sub>O and CH<sub>4</sub> emissions and carbon pool due to integrated crop-livestock in a subtropical Ferralsol *Agr. Ecosyst. Environ.* **190** 87–93
- Repo M E, Susiluoto S, Lind S E, Jokinen S, Elsakov V, Biasi C, Virtanen T and Martikainen P J 2009 Large N<sub>2</sub>O emissions from cryoturbated peat soil in tundra *Nat. Geosci.* **2** 189–92
- Robertson G P and Tiedje J M 1988 Deforestation alters denitrification in a lowland tropical rain forest *Nature* **336** 756–9
- Roelandt C, van Wesemael B and Rounsevell M 2005 Estimating annual N<sub>2</sub>O emissions from agricultural soils in temperate climates *Global Change Biol.* **11** 1701–11
- Santos J H G, Costa A R, Madari B E, Machado P L and Alves B J R 2008 *Emissao de oxido nitroso derivada do cultivo de feijoeiro comum (3ª safra) seguido de milho em latossolo de cerrado Documentos IAC Campinas* **85** 1125–8
- Shcherbak I, Millar N and Robertson G P 2014 Global meta-analysis of the nonlinear response of soil nitrous oxide (N<sub>2</sub>O) emissions to fertilizer nitrogen *Proc. Natl Acad. Sci. USA* **111** 9199–204
- Silver W L, Thompson A W, McGroddy M E, Varner R K, Dias J D, Silva H, Crill P M and Keller M 2005 Fine root dynamics and trace gas fluxes in two lowland tropical forest soils *Global Change Biol.* **11** 290–306
- Sordi A, Dieckow J, Bayer C, Albuquerque M A, Piva J T, Zanatta J A, Tomazi M, Machado da Rosa C and Moraes A 2014 Nitrous oxide emission factors for urine and dung patches in a subtropical Brazilian pastureland *Agr. Ecosyst. Environ.* **190** 94–103
- Sotta E D, Corre M D and Veldkamp E 2008 Differing N status and N retention processes of soils under old-growth lowland forest in Eastern Amazonia, Caxiua, Brazil *Soil Biol. Biochem.* **40** 740–50
- Steudler P A, Garcia-Montiel D C, Piccolo M C, Neill C, Melillo J M, Feigl B J and Cerri C C 2002 Trace gas responses of tropical forest and pasture soils to N and P fertilization *Global Biogeochem. Cy.* **16** 102–8
- Subbarao G V et al 2009 Evidence for biological nitrification inhibition in Brachiaria pastures *Proc. Natl Acad. Sci. USA* **106** 17302–7
- Tomasella J, Hodnett M G and Rossato L 2000 Pedotransfer functions for the estimation of soil water retention in Brazilian soils *Soil Sci. Soc. Am. J.* **64** 327–38
- Varella R F, Bustamante M M C, Pinto A S, Kisselle K W, Santos R V, Burke R A, Zepp R G and Viana L T 2004 Soil fluxes of CO<sub>2</sub>, CO, NO, and N<sub>2</sub>O from an old pasture and from native savanna in Brazil *Ecol. Appl.* **14** 221–31
- Varner R K, Keller M, Robertson J R, Dias J D, Silva H, Crill P M, McGroddy M and Silver W L 2003 Experimentally induced root mortality increased nitrous oxide emission from tropical forest soils *Geophys. Res. Lett.* **30** 114
- Vasconcelos S S et al 2004 Moisture and substrate availability constrain soil trace gas fluxes in an eastern Amazonian regrowth forest *Global Biogeochem. Cy.* **18** GB2009

- Veldkamp E, Davidson E, Erickson H, Keller M and Weitz A 1999 Soil nitrogen cycling and nitrogen oxide emissions along a pasture chronosequence in the humid tropics of Costa Rica *Soil Biol. Biochem.* **31** 387–94
- Verchot L V, Brienza S Jr, Costa de Oliveira V, Mutegi J K, Cattanio J H and Davidson E A 2008 Fluxes of CH<sub>4</sub>, CO<sub>2</sub>, NO, and N<sub>2</sub>O in an improved fallow agroforestry system in eastern Amazonia *Agr. Ecosyst. Environ.* **126** 113–21
- Verchot L V, Davidson E A, Cattanio J H, Ackerman I L, Erickson H E and Keller M 1999 Land use change and biogeochemical controls of nitrogen oxide emissions from soils in eastern Amazonia *Global Biogeochem. Cy.* **13** 31–46
- Vor T, Dyckmans J, Lotfield N, Beese F and Flessa H 2003 Aeration effects on CO<sub>2</sub>, N<sub>2</sub>O, and CH<sub>4</sub> emission and leachate composition of a forest soil *J. Plant Nutr. Soil Sci.* **166** 39–46
- Wick B, Veldkamp E, de Mello W Z, Keller M and Crill P 2005 Nitrous oxide fluxes and nitrogen cycling along a pasture chronosequence in Central Amazonia, Brazil *Biogeosciences Discussions* **2** 499–535