MISSING HOT MOMENTS OF GREENHOUSE GASES IN SOUTHERN AMAZONIA

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With 7 figures and 5 tables

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Summary: The superlative environmental conditions in Southern Amazonia, i.e. high temperatures and annual rainfall, create ideal conditions for high soil organic matter turnover rates and therewith the soil-atmosphere exchanges of greenhouse gases. In this study, we present daily observations of soil-related carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) emissions from the dominant land use types in Mato Grosso (cerrado, gallery forest, cattle pasture, and cropland under soybean) and Pará (rainforest and cattle pastures) during the early rain season. We followed the hypothesis that precipitation events provoke hot moments for CO_2 and N_2O, and lead to alternating uptake and emission for CH_4, respectively. Observed fluxes differed significantly between land use types and underlying soil type. CO_2 fluxes from soils under natural vegetation ranged from 101 mg m^{-2} h^{-1} in the cerrado to 160 mg C m^{-2} h^{-1} in the rainforest. Fluxes from cattle pastures varied between locations and were 79 mg C m^{-2} h^{-1} from the pasture in Mato Grosso and between 120 and 180 mg C m^{-2} h^{-1} from pastures in Pará. For N_2O, fluxes were highest from rainforest (16 μg N m^{-2} h^{-1}) and lowest from cerrado soil (-0.05 μg N m^{-2} h^{-1}). Similar to CO_2, the pastures in Pará emitted higher fluxes of N_2O (2–8 μg N m^{-2} h^{-1}) compared to the pasture in Mato Grosso (0.09 μg N m^{-2} h^{-1}). CH_4 fluxes were negative on all sites, except for two pasture sites in Pará, where recorded fluxes amounted to 10 and 53 μg C m^{-2} h^{-1}, respectively. The dynamic behavior during the measurement period, as determined by an indicator function, was moderate for N_2O, low for CO_2 and CH_4, and depended on the site and measurement chamber, respectively. Nevertheless, N_2O fluxes from the cropland increased during the end of the vegetation period of soybean, likely as a result of increased nitrogen availability due to ceasing plant roots. At the same time cattle pastures showed an age-related decrease of N_2O emissions, whereas they turned out to being considerable sources for CH_4. Generally, the low dynamics and missing reactions to precipitation events demonstrate poor process understanding and need to be further investigated.

Zusammenfassung: Die außergewöhnlichen Umweltbedingungen im südlichen Amazonasgebiet, z.B. hohe Temperaturen und Jahresniederschläge, begünstigen Umsatzprozesse der organischen Substanz im Boden und damit den Gasaustausch zwischen Boden und Atmosphäre. In dieser Arbeit zeigen wir täglich gemessene Emissionen von Kohlendioxid (CO_2), Lachgas (N_2O) und Methan (CH_4) aus Böden vorherrschender Landnutzungen in Mato Grosso (Cerrado, Galleriewald, Rinderweide und Sojaacker) und Pará (Regenwald und Rinderweiden) zu Beginn der Regenzeit. Wir nahmen an, dass Regenereignisse zu kurzfristig höheren Emissionen (hot moments) von CO_2 und N_2O führen und für CH_4 einen stetigen Wechsel von Emissionen und Aufnahme mit sich ziehen. Die gemessenen Flüsse unterschieden sich signifikant zwischen den Landnutzungen und dem Bodentypen. CO_2-Fluesse aus Böden unter natürlicher Vegetation lagen zwischen 101 mg C m^{-2} h^{-1} im Cerrado und 160 mg C m^{-2} h^{-1} im Regenwald. Flüsse von den Rinderweisen variierten zwischen den Standorten lagen bei 79 mg C m^{-2} h^{-1} auf der Weide in Mato Grosso und zwischen 120 und 180 mg C m^{-2} h^{-1} in Pará. Für N_2O waren die Flüsse im Regenwald am höchsten (16 μg m^{-2} h^{-1}) und im Cerrado am niedrigsten (-0.05 μg N m^{-2} h^{-1}). Ähnlich wie bei CO_2 emittierten die Weiden in Pará mehr N_2O (2–8 μg N m^{-2} h^{-1}) im Vergleich zu den Weiden in Mato Grosso (0.09 μg N m^{-2} h^{-1}). CH_4-Fluesse waren negative auf allen Flächen, ausser auf zwei Weiden in Pará, wo die Flüsse sich auf 10, bzw. 53 μg C m^{-2} h^{-1} beliefen. Die Flussdynamiken, die mittels einer Indikatorfunktion bestimmt wurden, waren mäßig für N_2O, gering für CO_2 und CH_4 und hingen stark von der Landnutzung und der jeweiligen Messhaube ab. Nichtsdestotrotz zeigten die N_2O-Flüsse auf dem Acker einen Anstieg zum Ende der Vegetationsperiode der Sojabohne, wahrscheinlich aufgrund der reduzierten Wurzelaktivität und dem dadurch höheren Angebot an verfügbarem Stickstoff. Zusätzlich dazu nahmen die mittleren N_2O-Flüsse der Rinderweiden mit deren Alter ab; gleichzeitig erwiesen sich die Weiden als erhebliche CH_4-Quelle. Insgesamt zeigen die geringen Dynamiken und die fehlenden Reaktionen auf Niederschlagsereignisse, dass die zugrundeliegenden Prozesse noch nicht ausreichend verstanden sind und weiterer Untersuchungen bedürfen.

Keywords: CO_2, N_2O, CH_4, land use, soil science, Brazil

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1 Introduction

In 2012, Brazil was ranked the second largest emitter of greenhouse gases (GHG) from land use change and deforestation and the third largest emitter from agriculture (FAO 2014). Due to the superlative environmental conditions, i.e. constantly high temperatures and annual precipitation amounts, the tropics are a highly productive system with fast nutrient cycles and, consequently, turnover rates. High input of water and organic matter are ideal conditions for soil-related emissions of greenhouse gases (GHG), such as carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4), whose production is strongly dependent on soil temperature, aerobic and/or anaerobic microbial processes, available oxygen (O_2), and soil moisture conditions, respectively (Keller and Reiners 1994; Liikanen et al. 2002; Ishizuka et al. 2002; Vor et al. 2003; Jungkunst et al. 2008). Surprisingly, in the review of Meurer et al. (2016a) it was found that N_2O emissions from Brazilian soils were low all over the country and emission peaks resulting from N inputs, such as fertilizer application, were rather moderate. However, included studies mainly provided data that was taken in bi-weekly resolution. Facing the high sensitivity of N_2O to external changes, it is very likely that important periods of higher emissions (hot moments, e.g. Mcclain et al. 2003), maybe due to heavy precipitation events, have been missed. Similar reactions can also occur for CH_4, which is known to be emitted from very moist soils but is consumed by microbes and thus absorbed from the atmosphere as soon as the soil drops a certain moisture level (Jungkunst et al. 2008). This uptake has been found for forest soils in various studies in tropical (e.g. Keller et al. 1983; Ishizuka et al. 2002; Kiese et al. 2003) and temperate climate (e.g. Butterbach-Bahl et al. 2002; Gundersen et al. 2012). CO_2 flux intensities were found to decrease with increasing soil moisture – however, rewetting processes and fast changes in soil moisture, as induced by heavy precipitation events followed by dry periods with high temperatures, might result in a dynamic behavior. On this account, observations in high temporal resolution covering the most apparent land use types are of high value. Since Southern Amazonia underlies distinct dry and wet seasons, the beginning and the end can be expected to be of interest, since they represent a transitional period from dry to wet and vice versa, respectively.

In this study, we present observations of the soil - atmosphere exchange of CO_2, N_2O, and CH_4 from different land use types during the early rainy season. Concerning the climatic and land use gradient of Southern Amazonia, our field campaigns focused sites around Campo Verde (Mato Grosso) and Novo Progresso (Pará). We followed the hypothesis that the precipitation events will lead to hot moments, which will mainly specify the emissions of N_2O. For CO_2, we expected rather steady fluxes and low dynamics – here, very high soil moistures might rather lead to shortly reduced emissions (cold moments). The high, but still varying soil moisture might trigger the emissions of CH_4 and lead to permanent alternations between uptake and emission. At the same time we consider the land use type as well as the underlying soil type having a strong impact on the emission levels.

2 Material and methods

2.1 Site description

The field studies concentrated on sites within the two Federal States Mato Grosso (MT) and Pará (PA) (Fig. 1). The states are traversed by the Cuiabá-Santarém highway BR-163, which functions as an export corridor for soybeans via the Amazon River (Fearnside 2007). In Mato Grosso, data collection was performed in the vicinity of Campo Verde (15.5667° S, 55.1689° W), east of Cuiabá. The dominant soil types of the sites were Arenosol and Ferralsol, as can be seen in table 1. In this area, cerrado, as natural vegetation, has widely been removed and the subsequently established cattle pastures have been converted into cropland to a large extent. However, selected study sites included natural vegetation (cerrado *stricto sensu* and gallery forest), as well as agricultural lands, such as a cattle pasture (21 years old) and cropland. Gallery forests represent about 5 % of the Cerrado area and they describe a typical vegetation formation along rivers (Felfili et al. 2001). Due to their strong position in the biogeochemical functioning of the Cerrado landscape (i.e. reducing erosion and filtering agrochemicals from adjacent cultivated areas) they are environmentally protected by the Brazilian Forest Code (Parron et al. 2011). The gallery forest in this study bordered the cattle pasture and a fence prevented the cattle to enter the forest. The cropland has been used as cattle pasture for 25 years before it was converted into arable land in 1995. The land is under a continuous corn-soybean rotation and no-tillage is the common management practice in this area. The data presented in this study cover the growth period of soybean. No additional ferti-

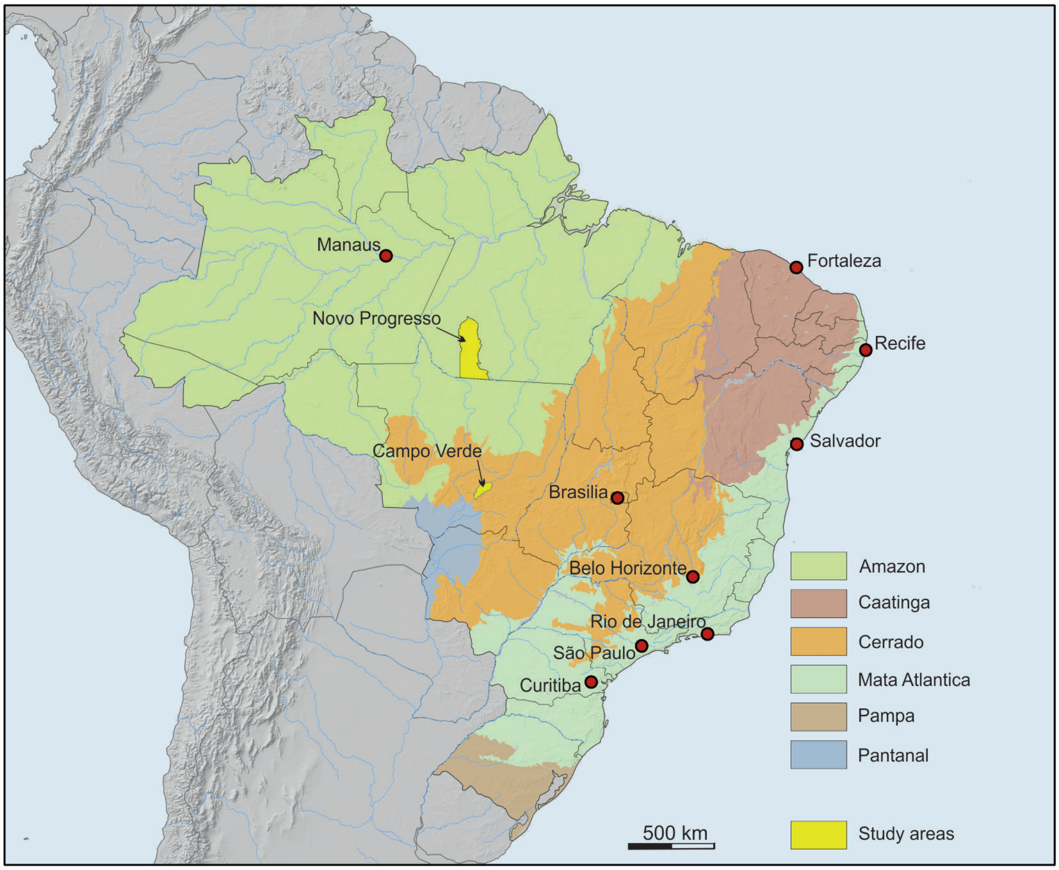

Fig. 1: Localization of the two study areas Campo Verde and Novo Progresso

lizer was applied, but towards the end of the soybean growth pesticides were applied.

In contrast to the already strong agricultural orientation of Mato Grosso, rainforest still covers large areas of the State Pará, but cattle pastures shape the landscape along the BR-163 highway. The village Novo Progresso (7.14694° S, 55.3819° W) developed directly along the highway. Here, measurements were conducted in the rainforest, as well as on three cattle pastures of different ages (years since conversion). Subsequently, they will be referred to as old (29 years), medium-aged (25 years), and young (12 years) pasture. Soil types at the sites were Acrisol and Ferralsol (Tab. 1).

2.2 Soil gas flux measurements

Greenhouse gas fluxes from the soil to the atmosphere were determined using the closed chamber approach following Flessa et al. (1995). The chambers were opaque, which means that photosynthesis was suppressed and observed CO_2 fluxes represent soil respiration. The ring which remained in the soil during the entire sampling period enclosed an area of 0.062 m^2; the corresponding chamber which was set on the ring in order to close the system and enable detection of soil gas exchange had a total volume of 0.016 m^3. Both parts were made of PVC. Gas samples were taken with a syringe and stored in pre-evacuated exetainer vials. Before each sampling, the air inside the chamber was mixed by a small fan (25 x 25 x 10 mm, 5.1 m^3 h^{-1}) which was activated from the outside. Pressure equilibration was enabled by a vent tube. The temperature inside the chamber was automatically recorded every minute. During the sampling time three samples were taken at 0, 45, and 90 minutes with five repetitions (chambers) per study site.

Trace gas analysis was carried out by a gas chromatography system consisting of an autosampler unit coupled online to a GC (APS 96/20-K, ESWE Gera Analysentechnik GmbH, Germany, coupled to a GC-14B, Shimadzu, Japan). Gas flux was calculated according to the increase or decrease of gas concen-

Tab. 1: Main characteristics of the different study sites and measurement periods. Soil variables refer to a depth of 0 - 10 cm.

	Land use type	Location	Soil type [WRB]	ϱ_b [g cm^{-3}]	C_{org} [%]	Clay [%]	pH [-]	Year of conversion	Measurement Period
Campo Verde (MT)	Cerrado	15.793583° S 55.338117° W	Arenosol [a)]	1.43	1.88	12	3.64	-	10/13 + 01/14
	Gallery forest	15.804786 ° S 55.337158 ° W	Arenosol	1.28	0.46 [b)]	10	3.72 [b)]	-	01/14 [c)]
	Pasture	15.804681° S 55.335222° W	Arenosol [a)]	1.49	1.42	5	4.45	1993	01/14 [c)]
	Cropland	15.72155° S 55.344767° W	Ferralsol [a)]	0.99	3.18	73	5.22	1995	10/13 – 02/14 [d)]
Novo Progresso (PA)	Rainforest	7.045275° S 55.366483° W	Acrisol [e)]	0.91	1.49	24			12/12 + 01/13 11 + 12/13
	Pasture								
	old	7.025536° S 55.376344° W	Acrisol [e)]	1.33	1.83	19	4.81	1984	12/12 – 02/13
	medium-aged	7.175108° S 55.369369° W	Ferralsol [e)]	1.05	2.39	44	5.07	1988	11 + 12/13
	young	7.184042° S 55.396075° W	Ferralsol [e)]	1.39	1.45	34	4.94	2001	11 + 12/13

[a)] Nobrega et al. (2015)
[b)] data refer to the depth 0–5 cm
[c)] two-daily sampling
[d)] sporadic data collection (8 times) during 11 + 12/13
[e)] Strey et al. (2016)

tration over time. All flux rates were corrected for air temperature and air pressure inside the chamber. In addition to that, soil moisture and temperature were detected using a TDR sensor.

Data was collected according to a daily sampling interval when possible. Thereby, the measurement sequence in terms of study sites was kept during the entire period and depended on the distance of the particular study site from the residence. This means that in Campo Verde, the cerrado was stopped at first, since it was furthest away, followed by the pasture and gallery forest, respectively, and the cropland at the end. In Novo Progresso, the first measurements were performed on the old pasture, followed by the rainforest in the first campaign (2012/2013), while during the second campaign (2013), the young pasture was followed by the medium-aged pasture and the rainforest.

2.3 Statistical analyses

Statistical analyses were conducted in R 3.0.2 (R Core Team 2013). Effects and differences of land use and soil type on GHG emissions were estimated by the non-parametric Kruskal-Wallis test of the R package *agricolae* (Mendiburu 2014). A paired t-test was used to prove differences between sites that were measured simultaneously. The influence of observed soil properties, including soil moisture and soil temperature was tested by linear regression. Since data derived from field measurements and thus do not underlie controlled conditions, differences were regarded significant for $p \leq 0.05$. Variation within the fluxes was expressed by the coefficient of variation (CV), which is a function of the mean value and the standard deviation within the specific dataset.

Since the data included a high background noise an indicator function was used as a rough evaluation of the daily mean values per site. Therewith it was determined whether a value exceeds or falls below the previously defined threshold τ, which is defined as a percentage of the standard deviation σ of the site-specific dataset. If the threshold is underrun or exceeded, the value is assigned 0 and 1, respectively. To overcome data gaps (days without measurements), the interpolation over the measurement period was done using a weighted moving average. In doing so, the weights of the moving average were determined by the temporal distance to the date for which the weighted moving average was calculated. A threshold of 0.5 · σ was used for all sites, with σ representing the standard deviation. The robustness of potential dynamic patterns was tested by comparison with a threshold of 0.7 σ. Flux dynamics was defined as an alternating exceedance and underrun of the threshold.

3 Results

Observed fluxes of CO_2, N_2O, and CH_4 from the different land use types are presented in Tab. 2. Both soil type and land use had significant impacts on emissions (Tab. 3).

Exclusion of climatic variations between the years by comparing areas that have been studied simultaneously (on the same day) showed that GHG fluxes from the gallery forest and the cropland did not differ significantly. However, emissions from both sites were significantly different to emissions from the cerrado. Likewise, emissions from rainforest were significantly different from the subsequent pastures, except for CO_2 fluxes between rainforest and young pasture (Tab. 4).

Linear regression with observed soil characteristics (independent from land use and soil type) showed rather weak relationships with CO_2 and CH_4 fluxes ($R^2 \leq 0.15$, Fig. 2). A significant correlation was only found for N_2O fluxes and bulk density ($R^2 = 0.63$).

3.1 Campo Verde

3.1.1 Soil parameters

The water-filled pore space was on average highest in the gallery forest (79–94 %, median: 88 %) and lowest in the cerrado (27–64 %, median: 55 %). In the cropland and pasture soils WFPS ranged between 50 and 69 %, and 54 and 64 %, respectively, and were 60 and 59 % on average. Except for the early measurements on the cropland, precipitation events did not markedly increase the WFPS. Although ϱ_b was lower in the cropland than in the cerrado (0.99 and 1.43 g m^{-3}, respectively), the soil under soybean was on average wetter. Due to the high clay content of the cropland (73 %) it can be expected that microaggregates have been formed – those have a loosening effect on the soil structure and therewith determine the hydraulic behavior of the soil. At the same time, water is held within the aggregates leading to a high water holding capacity. The average soil temperature was highest in the cropland (29 °C) and lowest in the cerrado and gallery forest (24 and 23 °C, respectively). Noticeable temperature variations only occurred on the cropland.

3.1.2 GHG fluxes

CO_2 fluxes were positive on all sites with only one exception on the cropland in the beginning of

Tab. 2: Minimum (Min), median (Med), and maximum (Max) of CO_2, N_2O, and CH_4 from soils under different land use in the municipalities Campo Verde (MT) and Novo Progresso (PA)

	Land use type	N	CO_2-C [mg m^{-2} h^{-1}]			N_2O-N [µg m^{-2} h^{-1}]			CH_4-C [µg m^{-2} h^{-1}]		
			Min	Med	Max	Min	Med	Max	Min	Med	Max
Campo Verde	Cerrado [a]	45	74	101	130	-5	- 0.05	9	-55	-27	3
	Gallery forest	11	100	115	138	0	4	8	-19	-4	12
	Pasture	11	54	79	94	-2	0.09	5	-23	-15	-12
	Cropland [a]	49	30	88	173	-11	6	18	-24	-10	6
Novo Progresso	Rainforest	48[b]	105	149	209	2	14	57	-44	-23	17
		48[c]	77	164	211	7	18	53	-50	-24	31
		96[d]	77	160	211	2	16	57	-50	-23	31
	Pasture										
	old	50	48	180	292	-3[e]	2[e]	18[e]	1	53	2518
	medium-aged	47	55	120	169	-1[e]	7[e]	32[e]	-34	-3	125
	young	49	81	173	264	1[e]	8[e]	52[e]	-51	10	81

[a] only 3 repetitions, [b] December 2012 + January 2013, [c] November + December 2013, [d] both periods,
[e] Meurer et al. (2016b), N = number of observations

Tab. 3. Results of Kruskal-Wallis rank sum test. Different letters indicate significant differences between groups for $p \leq 0.05$.

Factor	CO_2-C	N_2O-N	CH_4-C
Soil type			
Acrisol	a	a	b
Arenosol	c	c	c
Ferralsol	b	b	a
Land use			
Campo Verde			
Cerrado	d	f	f
Gallery forest	c	d	cd
Pasture	e	f	e
Cropland	e	cd	d
Novo Progresso			
Rainforest	b	a	f
Pasture			
old	a	e	a
medium-aged	c	bc	c
young	a	b	b

December (Fig. 3 and Fig. 4). Lowest CO_2 fluxes were observed on the pasture and highest median emissions were measured in the gallery forest (79 and 115 mg C m^{-2} h^{-1}, respectively). Despite the high fluxes, variation of CO_2 emissions from the gallery forest was lowest (CV = 10 %); highest variation was found in the cropland (CV = 35 %). Independent of the site, the fluxes did not show considerable dynamics, as shown by the indicator function. Except for one observation on the cropland, the data constantly exceeded the defined threshold (data not shown). CO_2 fluxes significantly correlated with soil moisture on the cropland (r = 0.35) and soil temperature in the cerrado (r = 0.39) and gallery forest (r = 0.68, Tab. 5).

N_2O fluxes were both positive and negative on all sites, except for the gallery forest, where only positive fluxes were observed. Here, we found a strong relationship to the soil temperature (r = 0.76). In general, N_2O emissions were low in the gallery forest and around zero in the cerrado and cattle pasture. Nevertheless, the latter two sides showed the highest variation in terms of N_2O fluxes, which accounted for 1,630 and 1,089 %, respectively. Data collection on the cropland covered the whole vegetation cycle of the planted soybean, starting directly after the planting and ending shortly before the harvest. On this plot, CO_2 and N_2O fluxes show similar trends of decreasing and constantly low emissions some weeks after the planting and increasing fluxes at the state of maturity (Fig. 3). N_2O fluxes were positive almost exclusively, and a negative response (in all chambers) was only observed on one day at the very end of the measurements and shortly after the application of pesticides in the cropland.

Compared to the CO_2 fluxes, N_2O reacted more dynamically on all sites. Strong dynamics were observed in all chambers of the gallery forest and the pasture – here, the increase of the threshold from 0.5 to 0.7 · σ did not lead to considerable changes in the patterns (data not shown). Generally, the WFPS explained 25 % of the variation within the N_2O fluxes on these two sites; however, the only significant correlation was found with the soil temperature in the gallery forest (r = 0.74).

As expected, CH_4 fluxes were almost constantly negative on the cropland, in the cerrado, and on the pasture. In the gallery forest, CH_4 was absorbed by the soil on average (Tab. 2), but the two-daily observations rather fluctuated around zero. The highest uptake of CH_4 was observed by the cerrado soil. Flux dynamics were low on all sites and only observed in one (cerrado), two (cropland) and three (gallery forest) chambers, respectively. No CH_4 dynamics were found on

Tab. 4. Results of pairwise t-test for GHG fluxes simultaneously studied sites. ns = no significant difference, * = $p \leq 0.05$.

Land use	CO_2-C	N_2O-N	CH_4-C
Cerrado – Cropland	*	*	*
Cerrado – Pasture	*	ns	*
Cerrado – Gallery Forest	*	*	*
Cropland - Pasture	ns	*	*
Cropland – Gallery Forest	*	ns	ns
Rainforest – old pasture	*	*	*
Rainforest – medium-aged pasture	*	*	*
Rainforest – young pasture	ns	*	*
Medium-aged pasture – young pasture	*	ns	ns

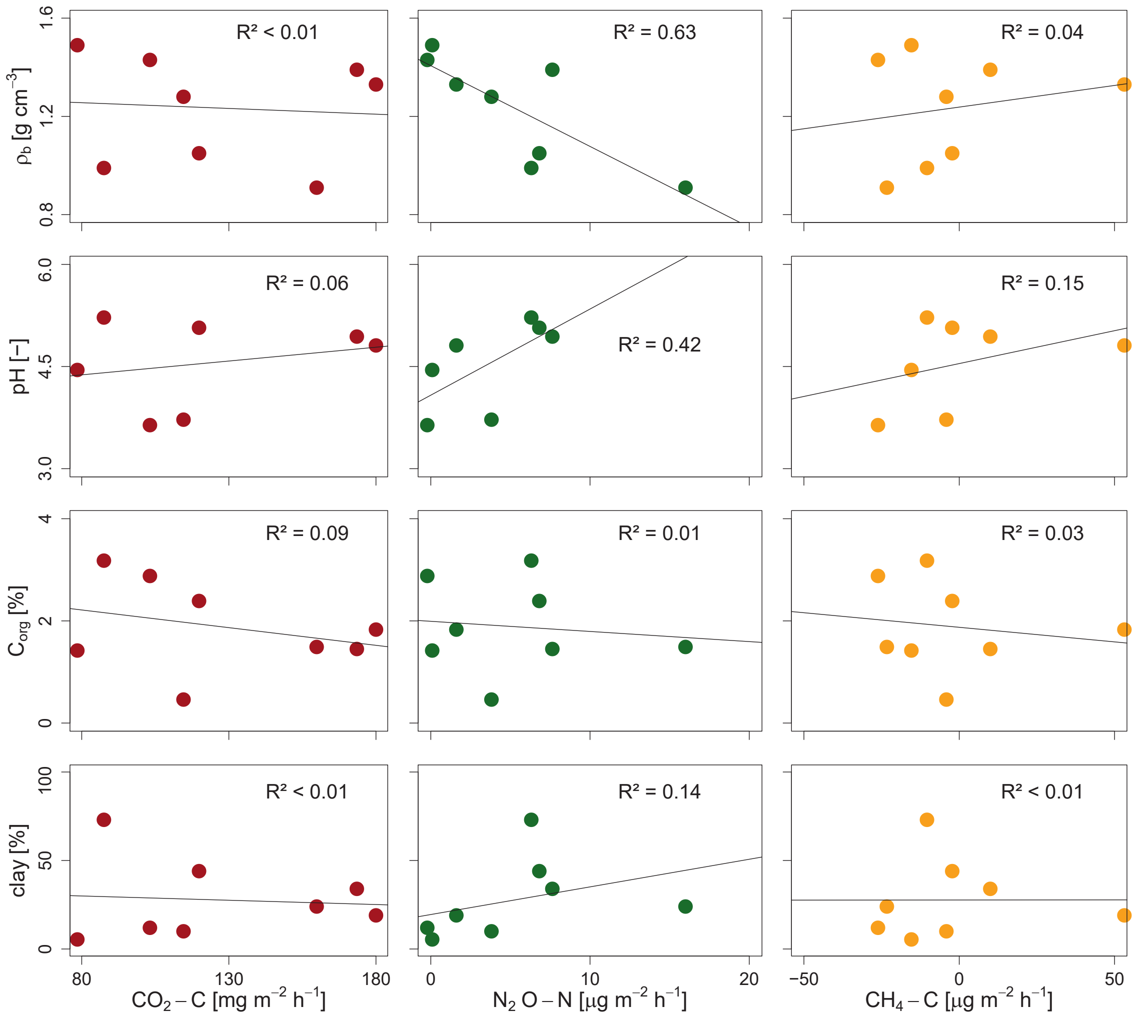

Fig. 2: Linear relationships between median GHG emissions and soil characteristics (ϱ_b, pH, C_{org}, and clay content). * = $p \leq 0.05$

the cattle pasture and daily fluxes constantly underran the threshold value. However, emissions correlated significantly with WFPS on the pasture site (r = 0.68) and in the cerrado (r = 0.33). A positive, but not significant linear relationship was also found with the soil temperature in the gallery forest (r = 0.51).

3.2 Novo Progresso

3.2.1 Soil parameters

In the rainforest, soil moisture fluctuated markedly and WFPS ranged from 20–67 %, with an average of 42 %. The pasture soils were generally wetter than the forest soil with highest WFPS on the old pasture (45–99 %, median: 69 %). In the medium-aged and young pasture WFPS were 61 % (56–67 %) and 64 % (57–73 %) on average. Average soil temperature ranged between 25 (young pasture) and 29 °C (medium-aged pasture). The lower temperatures that were observed on the young pasture compared to the medium-aged pasture result from the timing of the measurements; the young pasture was usually measured during the morning hours. Soil temperatures in the forest soil were below those of the medium-aged and old pasture (28 °C) and were 26 °C on average.

3.2.2 GHG fluxes

CO_2 and N_2O fluxes were positive on all sites and almost without exception (Fig. 5 and Fig. 6). CO_2 fluxes from the old and young cattle pastures

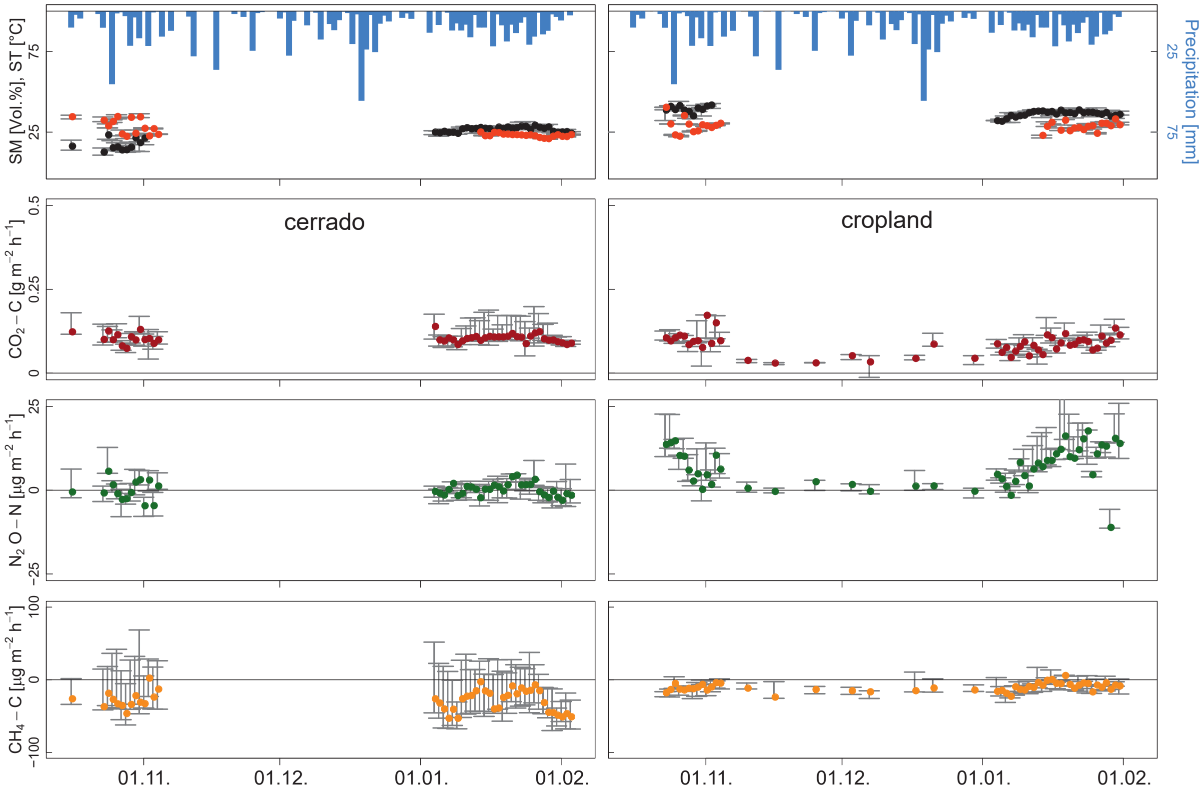

Fig. 3: Median values of soil moisture (SM, black), soil temperature (ST, red), and fluxes of CO_2, N_2O, and CH_4 from soils under cerrado (October 2013 + January 2014) and cropland (October 2013–February 2014). Bars represent minimum and maximum values.

were higher than from the forest site (180, 173, and 160 mg C m^{-2} h^{-1}, respectively). Lowest emissions were observed from the medium-aged pasture (120 mg C m^{-2} h^{-1}). On all pasture sites CO_2 fluxes correlated significantly positive with soil temperature and negative with WFPS, except for the young pasture (Tab. 5). Flux variations were moderate and ranged between 16 (rainforest) and 25 % (old pasture). Again, CO_2 fluxes did not show considerable dynamics and they exceeded the threshold value with one exception in chamber 4 on the medium-aged pasture.

In the rainforest, daily median N_2O fluxes were highest and positive without exception (16 µg m^{-2} h^{-1}); negative fluxes were only occasionally observed. On the pasture sites, fluxes were generally low and fluctuated around zero (positive and negative fluxes). However, highest average fluxes were found for the young (8 µg m^{-2} h^{-1}) and lowest for the old pasture (2 µg m^{-2} h^{-1}, Tab. 2). Dynamic patterns were found on each site and in all chambers – however, dynamics from the pastures were more pronounced compared to the rainforest (Fig. 7 in the appendix). N_2O fluxes correlated positively with soil temperature on the old and young pasture, and in addition negatively with WFPS on the old pasture.

The rainforest was a sink for CH_4 and the average uptake was 23 µg m^{-2} h^{-1}. Although fluxes from the medium-aged pasture were both positive and negative, CH_4 was taken up on average (-3 µg m^{-2} h^{-1}). This also applies to the young pasture, but there, average fluxes were positive (10 µg m^{-2} h^{-1}). Almost exclusively positive fluxes were observed on the old pasture; however fluxes increased at the end of the measurement period on all three pasture sites (Fig. 5 and 6). This runs contrary to the observations on the pasture in Campo Verde, where CH_4 was absorbed unexceptionally. Flux dynamics were stronger on the pasture sites compared to the rainforest, but they were strongly chamber dependent on the medium-aged and young pasture. CH_4 fluxes had significant relationships with soil temperature on none of the sites. However, fluxes correlated positively with WFPS in the rainforest (r = 0.32) and on the young pasture (r = 0.73).

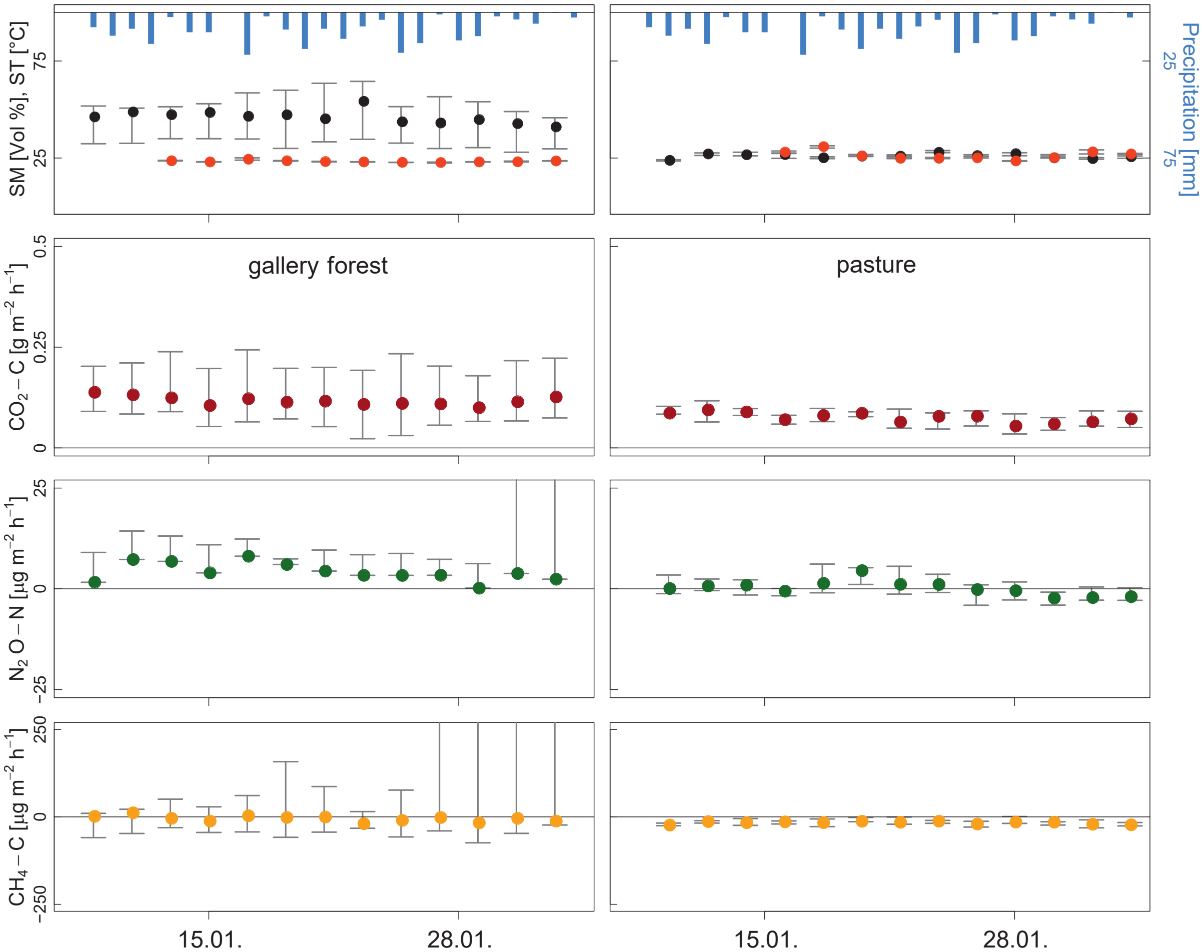

Fig. 4: Median values for soil moisture (SM, black), soil temperature (ST, red), and fluxes of CO_2, N_2O, and CH_4 from soils under gallery forest and cattle pasture (January 2014). Bars represent minimum and maximum values.

Tab. 5: Coefficients of correlation (r) between WFPS and temperature (temp) and fluxes of CO_2, N_2O, and CH_4 corresponding to the different locations and land use types. * = p ≤ 0.05.

Location	Land use type	CO_2-C		N_2O-N		CH_4-C	
		WFPS	temp	WFPS	temp	WFPS	temp
Campo Verde							
	Cerrado	0.14	0.39*	0.25	0.03	0.33*	-0.07
	Gallery forest [a)]	0.16	0.68*	0.55	0.74*	0.43	0.51
	Pasture	0.04	0.39	0.25	-0.01	0.69*	-0.27
	Cropland	0.35*	0.30	0.25	0.15	0.20	-0.13
Novo Progresso							
	Rainforest	0.18	0.19	-0.05	-0.02	0.32*	-0.005
	Pasture						
	old	-0.49*	0.49*	-0.42*	0.41*	-0.02	-0.03
	medium-aged	-0.45*	0.67*	0.20	-0.24	0.18	0.10
	young	-0.16	0.54*	0.18	0.66*	0.73*	0.19

[a)] excluding one value where WFPS > 100

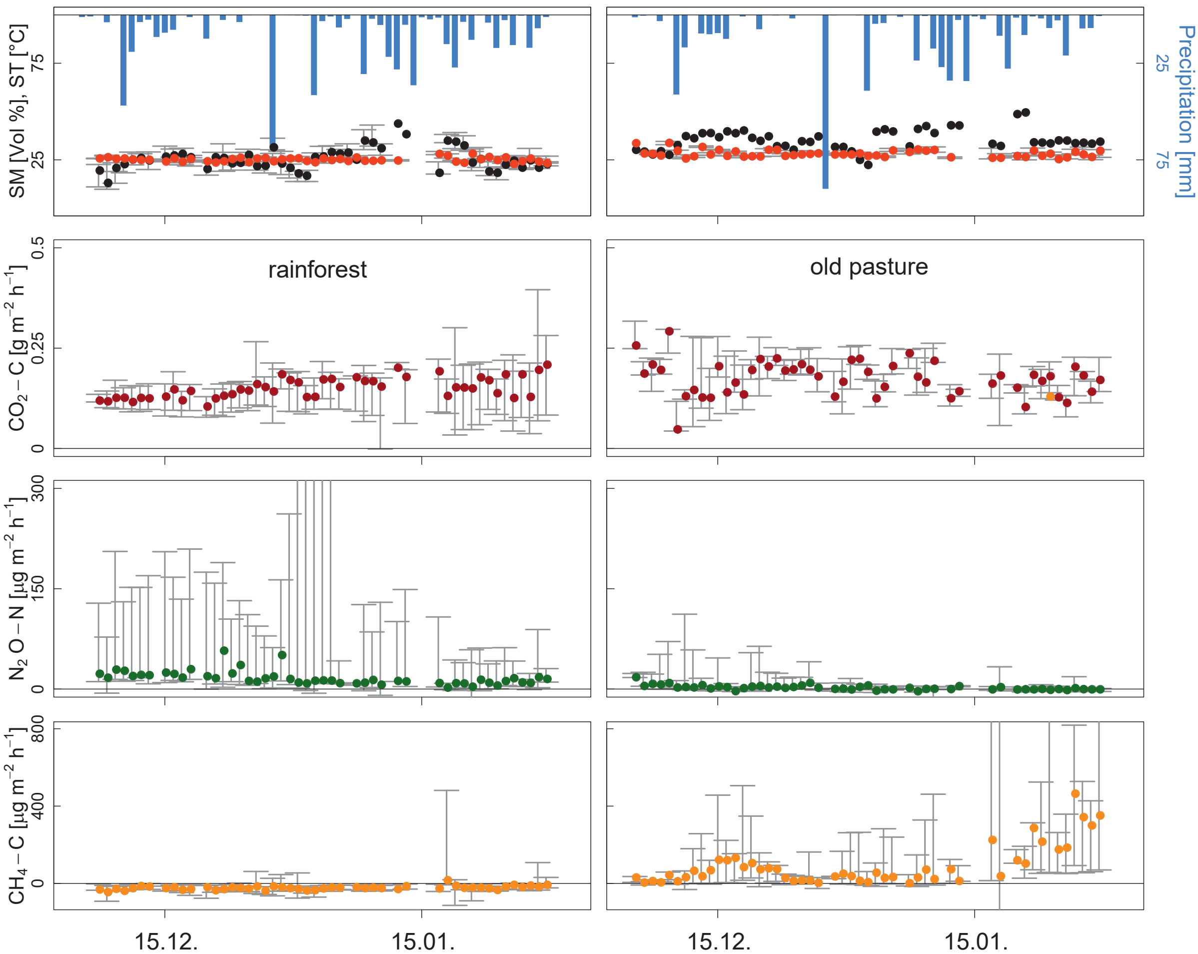

Fig. 5: Median values for soil moisture (SM, black), soil temperature (ST, red), and fluxes of CO_2, N_2O, and CH_4 from soils under rainforest and the old cattle pasture (MEURER et al. 2016b) (December 2012 + January 2013). Bars represent minimum and maximum values.

4 Discussion

4.1 CO_2 fluxes

CO_2 fluxes from soils under natural vegetation ranged from 103 mg C m^{-2} h^{-1} in the cerrado to 160 mg C m^{-2} h^{-1} in the rainforest. The observed fluxes exceed those reported from an open humid tropical forest in Brazil (139 mg C m^{-2} h^{-1}, Fernandes et al. 2002) and an old-growth lowland forest in Indonesia (63.3 mg C m^{-2} h^{-1}, Ishizuka et al. 2002) – however, it should be kept in mind, that the observation is a mix of heterothrophic and autothropic soil respiration. Additionally to the impact of the soil structure, the differences between CO_2 fluxes from soils under different natural vegetation might result from the relatively low vegetation biomass of cerrado (51.21 Mg ha^{-1}, Fearnside et al. 2009) compared to gallery forest (133 Mg ha^{-1}, Delitti and Burger 2000), and rainforest (264.4 Mg ha^{-1}, Lima et al. 2012). As a result, the turnover rate of the carbon cycle is relatively low in the cerrado, which may result in lower CO_2 fluxes (Ishizuka et al. 2002). Soil respiration from the pasture in the cerrado biome was lower than from the native vegetation, which follows findings of Neto et al. (2011) in a cerradão in Rio Verde, Goias. In contrast to this, emissions of CO_2 from the old and young pasture in Novo Progresso were higher than from the rainforest soil. These results follow findings of Feigl et al. (1995) in two forest-to-pasture chronosequences in Rondônia during the dry season. In their study, the authors found that CO_2 emissions increased with pasture age up to 9 years, but not beyond. Our dataset does not include enough pastures of different ages to give a clear statement on this. However, using the four pastures of this study, we did not find a relationship between CO_2 fluxes and pasture age.

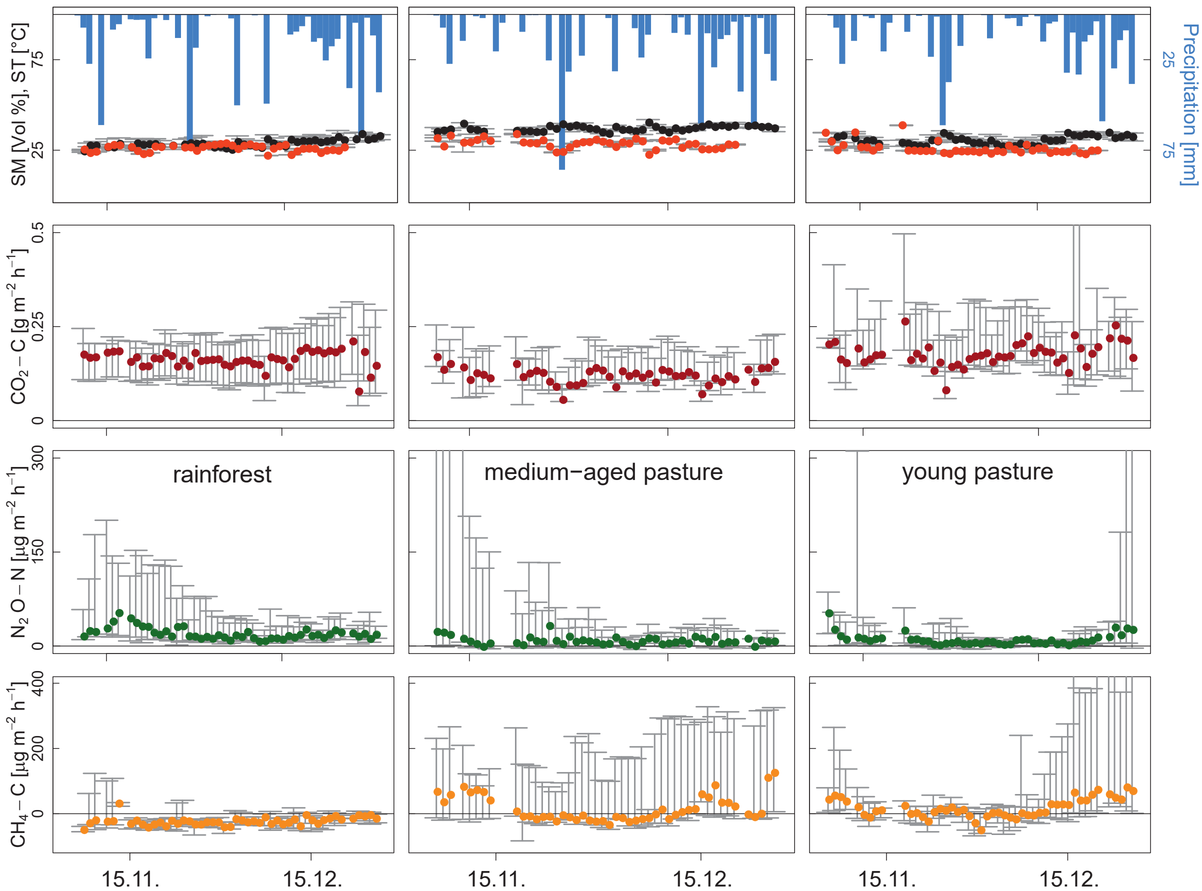

Fig. 6. Median values for soil moisture (SM, black), soil temperature (ST, red), and fluxes of CO_2, N_2O, and CH_4 from soils under rainforest, a medium-aged and a young cattle pasture (November + December 2013). Bars represent minimum and maximum. N_2O data from the pastures derive from Meurer et al. (2016b).

Generally, C mineralization and soil CO_2 emissions are known to be stimulated by drying and rewetting cycles (Sørensen 1974) and WFPS, respectively. As WFPS increases, O_2 diffusion gets limited in the soil matrix, which favors denitrification. As a result, CO_2 emissions can be expected to decrease, as already shown by Maggs and Hewett (1990) and Davidson et al. (1998). The latter found a positive relationship between CO_2 and soil moisture for dry conditions ($\leq$ 0.12 cm^3 cm^{-3}), but a negative correlation under higher soil moisture. However, since CO_2 is also produced during denitrification, reduced CO_2 emissions at decreasing O_2 availability only applies for sites with a general low denitrification capacity. In this study, negative correlations with WFPS were only found for the pastures in Novo Progresso. Additionally, soil temperature explained between 49 and 67 % of the variability of the carbon fluxes on these sites. Measured soil characteristics did not seem to have a great impact on CO_2 fluxes, as we did not find clear relationships between emissions and ϱ_b, pH, C_{org} or clay. However, soil type and land use strongly affected carbon fluxes.

In this study, usage of an indicator function revealed that there were no noticeable dynamics in soil respiration. The variation within the daily CO_2 observations was high and on all sites the given threshold of 0.5 σ was exceeded in most of the chambers. The applied measurements technique gives no possibility to separate the CO_2 evolved from heterotrophic respiration from which results from soil organic matter mineralization. Therefore, the results do not provide a complete picture about the contribution of this important carbon pool to the GHG balance.

4.2 N_2O fluxes

Nitrous oxide fluxes from soils under natural vegetation were highest from the rainforest (16 µg m^{-2} h^{-1}). Observed fluxes were within the range of other studies in Amazonia, but far below emissions reported from tropical forest in Australia (e.g. KIESE et al. 2003). LIVINGSTON et al. (1988) and VERCHOT et al. (1999) reported on emissions of 11 and 28 μg N_2O-N m^{-2} h^{-1}, respectively, from forest sites in Amazonia. Thereby, VERCHOT et al. (1999) highlighted the difference between seasonal variations and differences between wet and dry season, respectively. They observed higher fluxes in the wet compared to the dry season (52.3 and 10.4 μg m^{-2} h^{-1}, respectively). In contrast to rainforests, reported N_2O fluxes from cerrado soils were rather low (e.g. 3.94 μg N m^{-2} h^{-1}, CARVALHO et al. 2014), very often below the detection limit (e.g. PINTO et al. 2002, ANDERSON and POTH 1998), and did not react to simulated precipitation (PINTO et al. 2002) or burning events (ANDERSON and POTH 1998). However, CARDOSO et al. (2001) found higher fluxes during the rainy season from October to May (9.17 μg m^{-2} h^{-1}), compared to the dry season covering June until September (8.46 μg m^{-2} h^{-1}), with annual average fluxes of 8.93 μg N m^{-2} h^{-1}. Fluxes presented in this study ranged from -5 to 6 μg N_2O-N m^{-2} h^{-1}, but were slightly negative on average (-0.05 μg N_2O-N m^{-2} h^{-1}).

N_2O fluxes from pastures differed significantly from each other, except for the young and medium-aged pastures ($p = 0.23$). Including all four pastures into the analysis of an age-related emission change did not result in a clear trend, as found by MELILLO et al. (2001), WICK et al. (2005), NEILL et al. (2005), or MEURER et al. (2016a). By just focusing on the three cattle pastures from Novo Progresso which were significantly higher in clay content compared to the pasture in Campo Verde, it appears that median N_2O fluxes decreased with increasing pasture age. This furthermore highlights the importance of soil properties and previous land use type and natural vegetation, respectively. Lowest emissions were observed from the pasture that has been under cerrado vegetation before, whereas emissions from an older pasture converted from rainforest were significantly higher. MELILLO et al. (2001) and PINTO et al. (2006) both reported on higher N_2O emissions from previously converted cattle pastures compared to the natural rainforest and cerrado vegetation, respectively. Although average fluxes from cattle pastures in cerrado areas were higher than from pastures in rainforest areas (2-year old pastures: 51 μg N m^{-2} h^{-1} (rainforest) vs. 95 μg N m^{-2} h^{-1} (cerrado), 4-year old pastures: 19 μg N m^{-2} h^{-1} (rainforest) vs. 16 μg N m^{-2} h^{-1} (cerrado)), PINTO et al. (2006) pointed out that these emissions mostly resulted from one single collar where high emissions were measured and that emissions from the pastures were below the detection limit in general. In this study, N_2O fluxes from the cropland were low (10 μg N m^{-2} h^{-1} on average), but showed an increase at the end of the vegetation period of soybean. YANG and CAI (2005) showed in a pot experiment that up to 94 % of the total N_2O emissions from soils planted with soybean take place during the comparatively short period from grain-filling to ripening. They concluded that during this stage, plant roots cease growing whereby soil nitrogen uptake decreases. Additionally, available nitrogen is released into the soil from decaying roots and N rich nodules which results in N_2O production and emissions. Besides the N_2O increase our observations include one emission decline, which was found in all chambers in the cropland. Four days before that observation, pesticides were applied in the cropland, which might have a delayed effect on the nitrogen cycles of the soil.

In this study, N_2O fluxes correlated positively with soil temperature in the gallery forest and on the old and young cattle pasture. At the same time, fluxes negatively correlated with water-filled pore space on the old pasture. Here, the highest N_2O flux was measured at a WFPS of 60 %. All in all, the soil was very wet on this site and WFPS below 60 % were observed only on 7 days.

Although no direct reaction to precipitation events could be observed, N_2O turned out to be the most dynamic compound of all three gases. This indicates the necessity for a stronger research focus on underlying processes and closer investigation of the missing hot moments.

4.3 CH_4 fluxes

Methane was on average taken up by the soils at all sites, excluding the old and young cattle pasture in Novo Progresso. Highest uptake rates were found in the cerrado and the rainforest (-36 and -23 μg C m^{-2} h^{-1}, respectively), while lowest rates were observed in the gallery forest and on the medium-aged pasture in Novo Progresso (-4 and -3 μg C m^{-2} h^{-1}, respectively). Uptake of CH_4 by forest soils has widely been observed (e.g. KELLER et al. 1986; POTH et al. 1995; STEUDLER et al. 1996; NETO et al. 2011). Taking the remaining natural rainforest and cerrado vegetation of the Legal Amazon as a basis (3.181.706 and 581.282 km², respectively), annual uptake of atmospheric CH_4-C would account for 0.64 and 0.13 Mt ha^{-1} by rainforest and cerrado soils.

Emissions from the old and young pastures were 53 and 10 μg C m^{-2} h^{-1} on average which turns them into CH_4 sources. Similar results have been found by Steudler et al. (1996) in two tropical forest-to-pasture chronosequences in the Amazon Basin. In their study they found WFPS a strong predictor for CH_4 exchange. While pasture soils are usually compacted as a result of cattle grazing, they have reduced air-filled pore space, which favors CH_4 production by methanogens. In contrast to this, forest soils usually do not reach such high WFPS and, consequently, rather consume atmospheric CH_4. In this study, we found a good correlation between WFPS and CH_4 fluxes in the rainforest, the cerrado and on two pastures (Tab. 5).

Fluxes were positive and negative at all sites, except for the cattle pasture in Campo Verde where fluxes were negative in general. However, this fluctuation shows that the flux itself is a product of production and consumption within the soil (Ishizuka et al. 2002), which highlights the importance of soil texture characteristics as key factors of gas transport and microbial activity. Though, we did not find significant correlations between CH_4 fluxes and soil properties. Based on these results, we can assume that the type of land use and ecosystem (Dutaur and Verchot 2007) is the main driver of CH_4 fluxes. This can even be confirmed by the CH_4 dynamics which were mainly found for the sites in Novo Progresso (rainforest and cattle pastures), and only sporadically appeared in single chambers on the sites in Campo Verde (cerrado biome). Additionally, a clear difference between the natural and anthropogenically influenced areas could be made, since the dynamics were more pronounced on the pastures compared to the rainforest.

The order of average fluxes for all sites, corresponding to the location was:

Campo Verde

CO_2 emissions: gallery forest → cerrado → cropland → pasture

N_2O emissions: cropland → gallery forest → pasture → cerrado

CH_4 uptake: cerrado → pasture → cropland → gallery forest

Novo Progresso

CO_2 emissions: old pasture → young pasture → rainforest → medium-aged pasture

N_2O emissions: rainforest → young pasture → medium-aged pasture → old pasture

CH_4 uptake: rainforest → medium-aged pasture → young pasture → old pasture

The results presented give valuable hints for process understanding rather than budgeting, since they only include short periods and do not cover a whole year. In addition to that, presented data does not account for GHG losses during the actual land conversion. However, this intervention can be expected to result in CO_2 losses that are of magnitudes higher than the natural exchange between soil and atmosphere. Besides the loss of biodiversity and a large carbon pool, our results suggest that conversion of rainforest to cattle pasture turns the system from a CH_4 sink into a CH_4 source. However, only focusing on the land use and ecosystem might be inappropriate, since the soil type appeared to play an important role and substantially affect GHG fluxes. Significant differences between soil types were also reported by Keller et al. (2005), who found significantly higher N_2O fluxes from a clay compared to a sandy soil. Of the three soil types covered by this study, the Ferralsol and the Acrisol are the most common soil types in Amazonia (Quesada et al. 2011).

5 Conclusion

Despite differences in soil type and texture, fluxes and dynamics of CO_2, N_2O, and CH_4 from studied sites were low. Although both land use and soil type influence GHG fluxes, individual soil parameters which are known to drive GHG fluxes, e.g. bulk density, pH, C_{org} and clay content, were found being poor predictors on the studies sites. Independent of that, site-specific dynamics represented the high heterogeneity of the soil, which can hardly be covered by manual measurements. Based on the data presented here, we cannot evaluate whether the soil type, the ecosystem or the current land use has the highest impact on resulting GHG fluxes. However, we strongly recommend consideration in future field campaigns and long-term observations, respectively.

Generally, soil under rainforest emitted similar amounts of CO_2 compared to the subsequent cattle pastures in Novo Progresso, which still contained almost the same amount of soil carbon as the natural vegetation. Natural sites were sinks for CH_4, except for the comparatively wet gallery forest, but this effect changed after conversion and the uptakes from the pasture and cropland in Mato Grosso were only half and one third the uptake of the cerrado. Conversion of rainforest into cattle pastures even turned the soil from a CH_4 sink into a source. Opposite to that, N_2O fluxes were lower from pastures compared to rainforest. Nevertheless, these results represent sites that have been under the specific land use since a longer time and nothing is known about the short period around the conversion process. Soil disturbances of this kind can be expected to result in high short-term emissions. Still, the underlying processes for the missing emission peaks following external changes are poorly understood and require further investigation. If these findings can be confirmed, Brazil may be downgraded in the GHG ranking concerning agriculture.

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