https://doi.org/10.5194/bg-2020-86
Preprint. Discussion started: 20 April 2020

Biogeosciences Discussions
Open Access

Seasonality of greenhouse gas emission factors from biomass burning in the Brazilian Cerrado

Roland Vernooij[1], Marcos Vinicius Giongo Alves[2], Marco Assis Borges[3], Máximo Menezes Costa[3], Ana Carolina Sena Barradas[3], Guido R. van der Werf[1]

[1]Department of Earth Sciences, Faculty of Science, Vrije Universiteit Amsterdam, Amsterdam, The Netherlands
[2]Center for Environmental Monitoring and Fire Management (CEMAF), Federal University of Tocantins, Gurupi, Brazil
[3]Chico Mendes institute for Conservation of Biodiversity (ICMBio), Rio da Conceição, Brazil

Correspondence to: Roland Vernooij (r.vernooij@vu.nl)

Abstract. Landscape fires, often referred to as biomass burning (BB), emit substantial amounts of (greenhouse) gases and aerosols into the atmosphere each year. Frequently burning savannas, mostly in Africa, Australia, and South America are responsible for over 60% of total BB carbon emissions. Compared to many other sources of emissions, fires have a strong seasonality. Previous research has identified the mitigation potential of prescribed fires in savanna ecosystems; by burning early in the dry season when the vegetation has not fully cured, fires are in general patchier and burn less intense. While it is widely accepted that burned area and the total carbon consumed is lower when fires are ignited early in the dry season, little is known about the seasonality of emission factors (EF) of greenhouse gases. This is important because potentially, higher EFs in the early dry season (EDS) could offset some of the carbon benefits of EDS burning. Also, a better understanding of EF seasonality may improve large-scale BB assessments, which to date rely on temporally-static EFs. We used a sampling system mounted on an unmanned aerial vehicle (UAV) and cavity ring-down spectroscopy to estimate CO2, CO, CH4, and N2O EFs in the Estação Ecológica Serra Geral do Tocantins in the Brazilian states of Tocantins and Bahia. The protected area contains all major Cerrado vegetation types found in Brazil, and EDS burning was implemented on a large scale since 2014. We collected and analyzed over 800 smoke samples during the EDS and late dry season (LDS). Averaged over all measurements, the modified combustion efficiency (MCE) was slightly higher in the LDS (0.976 vs 0.972) and the CH4 and CO EFs were 13% and 15% lower in the LDS compared to the EDS. This seasonal effect was larger in more wood-dominated vegetation types. N2O EFs showed a more complex seasonal dependency, with opposite seasonal trends for savannas that were dominated by grasses versus those with abundant shrubs. We found that the N2O EF for the open cerrado was less than half of those reported so far in the BB literature for savannas. This may indicate a substantial overestimation of the contribution of fires in the N2O budget. Overall, our data implies that in this region, seasonal variability in greenhouse gas emission factors may offset only a small fraction of the carbon mitigation gains in fire abatement programs.

https://doi.org/10.5194/bg-2020-86
Preprint. Discussion started: 20 April 2020

Biogeosciences Discussions
Open Access

1. Introduction

Landscape fires emit large amounts of greenhouse gases and aerosols, which significantly impact atmospheric chemistry and biogeochemical cycles on local to global scales (Andreae and Merlet, 2001; Reid et al., 2005; van der Werf et al., 2017). The primary greenhouse gases emitted from biomass burning are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Over the period 1997–2016, average total annual emissions of these greenhouse gas from landscape fires was 7.3 Pg CO_2, 16 Tg CH_4, and 0.9 Tg N_2O according to the Global Fire Emissions Database (GFED4s, Van der Werf et al., 2017). Tropical savannas accounted for the majority of these global landscape fire emissions with 4.9 Pg CO_2, 6 Tg CH_4, and 0.6 Tg N_2O. South American savannas on average accounted for about 10% of the global savanna-, and thus 6.5% of the total fire-related carbon emissions over this period. In general, biomass burning CO_2 emissions are compensated for by regrowth of vegetation after the fire (Beringer et al., 2007; Landry and Matthews, 2016). Therefore, fires only impact long-term atmospheric CO_2 concentrations when regrowth does not take place (e.g., following deforestation and tropical peatland fires) or if fire regimes change. Carbon monoxide (CO) is generally not considered in carbon schemes (Cook et al., 2015; Lipsett-Moore et al., 2018). However, it reacts with atmospheric OH radicals and is eventually oxidized to CO_2 (Crutzen and Zimmermann, 1991). The depletion of OH radicals by CO leads to an increase in the atmospheric lifetime of CH_4 and the formation of ozone (O_3) (Crutzen and Zimmermann, 1991; Fry et al., 2012; Sudo and Akimoto, 2007). Therefore, CO can be viewed as an indirect greenhouse gas, more potent than CO_2 (Myhre et al., 2013).

Emission factors (EFs) are used to quantify the conversion of the total amount of carbon and other elements in the consumed fuel to emissions of various trace gases and aerosols. They are often reported in grams per kg of dry biomass consumed. Biomass burning EFs are derived from laboratory, ground-based, and aircraft measurements and have been reported for a large number of chemical species and vegetation types (Akagi et al., 2011; Andreae, 2019; Andreae and Merlet, 2001). The modified combustion efficiency (MCE), defined as the amount of carbon emitted as CO_2 divided by the amount of emitted carbon in CO_2 and CO combined, is often used as an indication of the relative contribution of flaming and smouldering combustion (Akagi et al., 2011). The MCE ranges from about 0.65 in smouldering peat fires to values close to one for highly efficient grass fires. The MCE is negatively correlated with EFs for incomplete combustion products such as CH_4, non-methane hydrocarbons (NMHC) and carbonaceous particulate matter (CPM) (Hoffa et al., 1999; Urbanski, 2013), making it a useful metric for emission estimations.

A substantial amount of research has been conducted to understand what environmental factors affect the EFs for greenhouse gases (e.g., Urbanski, 2014). While the drivers of variability in CO_2 and CH_4 EFs have received considerable attention, relatively little is known about the BB contribution to the N_2O budget. N_2O is formed through the oxidation of HCN and NH_3, in which the reaction of HCN through NCO is the dominant pathway. The N_2O EF is strongly dependent on the C:N ratio in the fuel (Lobert and Warnatz, 1993) as well as the temperature and partial pressure of oxygen during combustion (Kilpinen

https://doi.org/10.5194/bg-2020-86
Preprint. Discussion started: 20 April 2020

Biogeosciences Discussions
Open Access EGU

and Hupa, 1991; Winter et al., 1999a). CH_4 is formed during incomplete oxidation of biomass, with higher EF when the moisture content of the fuel is high (Chen et al., 2010), or when fuels are densely packed (Bertschi et al., 2003; Urbanski, 2013). While some of the drivers of variability in these EFs are qualitatively known, large-scale studies have so far relied on biome-average estimates due to the lack of quantitative information, thus ignoring spatio-temporal variability within biomes (Van Leeuwen and Van der Werf, 2011).

The Cerrado in South America consists of a mosaic of grasslands, shrublands, and forests. The biome covers roughly 24% of Brazil, and smaller parts of Paraguay and Bolivia (Klink and Machado, 2005). Vegetation dynamics and distribution are primarily determined by water availability, soil type and fire history (Pivello, 2011). The Cerrado can be categorized based on the abundance of woody species, ranging from campo limpo (open grassland), campo sujo (grassland with sparse presence of shrubs), campo rupestre (rock field), parque cerrado (grass/shrub-dominated with scattered trees), cerrado típico (tree-dominated with scattered shrubs and a grass understory) to cerradão (tree dominated). Forested landscapes are found in riparian zones within the Cerrado and are particularly fire-sensitive (Ribeiro and Walter, 1998). These riparian zones often comprise gallery forest that tend to directly line the river. Humid grasslands are also found here, consisting of gleysols that remain flooded in the rain season typically covered with grass and sparse palm trees. Fires have a dominant role in limiting the proportion of trees in the Cerrado, and fire frequencies generally range from 3 to 8 years (Fidelis et al., 2018). Natural fires in the Cerrado are caused by lightning and mostly occur in the beginning and end of the dry season. Anthropogenic fires, lit for example for cattle ranging pasture improvement, typically occur around the middle of the dry season in July-August (Pivello, 2011; Ramos-Neto and Pivello, 2000). Fire intensity is a key landscaping factor that can also feedback on vegetation state; high-intensity fires limit tree cover and promote open grassland formation, which in turn promotes higher fire frequency (Miranda et al., 2009; Oliveras et al., 2013; Staver et al., 2011).

Many grass species in the Cerrado dry out and senesce during the dry season, leading to standing dead fuel accumulation (Fidelis and Fernanda, 2013). Local practices have relied on prescribed burning in the past, and scientific research showed that fire has a key role in maintaining the Cerrado's high biodiversity. However, a 'zero-fire' policy has been maintained in the Brazilian Cerrado for decades (Durigan et al., 2016). While fire suppression strategies can be effective as a tool to enhance carbon sequestration and total carbon stocks (Murphy et al., 2010; Staver et al., 2011), keeping fire out of the Cerrado all together potentially leads to a sharp decline in biodiversity through the loss of light-demanding savanna species (Abreu et al., 2017; Durigan et al., 2016). In larger continuous landscapes, fire suppression strategies have led to a shift towards more high-intensity LDS fires that are more difficult to suppress. Frequent, high-intensity fires can cause long-term losses of soil nitrogen and phosphorous (Kauffman et al., 1994), which in turn decreases the total amount of carbon that is sequestered by net primary productivity. This may in time alter the carbon sink capacity of frequently burning savanna grasslands (Pellegrini et al., 2018). To combat the rise of intense LDS fires, it is important to look for alternative fire management strategies. Somewhat ironically, fire exclusion experiments have thus shown that well-managed fire intervals and intensities are vital for sustaining biodiversity in fire-prone savanna systems (Abreu et al., 2017; Durigan et al., 2016; Scott et al., 2012).

Given that fire exclusion and thus a fire-free Cerrado is hardly possible nor beneficial, previous studies have suggested the potential for prescribed burning in the EDS as an alternative to devastating LDS fires. In the EDS, the vegetation is still relatively humid leading to less intense fires (Rissi et al., 2017). For this reason, prescribed EDS burning is suggested as a climate mitigation strategy in the savanna (Lipsett-Moore et al., 2018; Penman et al., 2011; Russell-Smith et al., 2017; United Nations University, 2015). This extends the traditional view on fire management -governing the frequency of savanna burning- to one that also controls the timing of ignition within the fire season. This way, fire management may better dictate the impact of fire on the landscape. EDS fires clear away grass, litter and woody debris, but leave most shrubs and trees intact. As a result, the more damaging LDS are less likely to spread. Over time, prescribed EDS fire management allows trees to reach a height where the branches are less susceptible to fire.

Africa and South America combined collectively account for about 65–77% of the fire-prone savannas, and carbon-schemes may provide income alternatives to more destructive land management as shown in Australia (Lipsett-Moore et al., 2018; Maraseni et al., 2016; Russell-smith et al., 2017). Wildfire emissions are the product of fire extent, fuel load, combustion completeness, and EFs for the emitted species. It is widely accepted that when fires are ignited in the EDS, fires are smaller and more patchy (Oliveira et al., 2015), and the combustion completeness is lower (Price et al., 2012). Total fuel consumption is therefore lower. However, through more incomplete combustion under more humid conditions, higher CH_4 EFs could offset some of the climate gains from the reduced fuel consumption (Hoffa et al., 1999; Ito and Penner, 2004; Korontzi, 2005; van Leeuwen and van der Werf, 2011; Yokelson et al., 2011). Understanding and quantifying the seasonality in EFs is therefore essential to assess the implications of natural- and human-induced fire regime shifts.

In this study we have used a novel UAV-based approach to sample fires during three field campaigns, covering different parts of the dry season and various fire-prone Cerrado vegetation types. Our main objective was to assess the spatio-temporal variability in EFs for the main greenhouse gases associated with BB. With this knowledge we are in a better position to understand the carbon mitigation potential of savanna fire management and these findings may improve the representation of EFs in large-scale fire databases.

https://doi.org/10.5194/bg-2020-86
Preprint. Discussion started: 20 April 2020

2. Methodology

2.1 Study area

The Estação Ecológica Serra Geral do Tocantins (hereafter referred to as EESGT) is a protected area located in the Brazilian states of Tocantins and Bahia (Fig. 1a). With about 700,000 hectares, it is one of Brazil's largest ecological stations; a type of protected area established to preserve untouched representative samples of the different biomes in Brazil. EESGT used to be one of the most frequently burning protected areas in the Cerrado. On average, about 30% of the protected area burned each year (Fidelis et al., 2018). Since 2014, prescribed EDS burning is used within EESGT as a tool to reduce the negative impacts from uncontrolled, high-intensity LDS fires. The strategy focusses on creating a mosaic of smaller areas with different fire histories (Silva et al., 2005). Since 2014, the strategy has led to an increase in the number of fires but a decrease in average fire size and total burned area (Fidelis et al., 2018; Schmidt et al., 2018). This in contrast to other protected areas in the Cerrado, without sizable prescribed burning policies in place, most of which experienced an increase in burned area over the past decade. For example, nearby Chapada dos Veadeiros and Reserva Natural Serra do Tombador burned for 78% and 85% in 2017, respectively, inciting calls for wider implementation of EDS fire management (Fidelis et al., 2018).

EESGT has a semi-arid to tropical climate with two well-defined seasons. Hot and dry in May to September with maximum daily temperatures of 38ºC, and wet and cooler in the rainy season between October and April, when the temperature can drop to 21ºC and the average rainfall reaches over 7 mm/day (Fig. 2a). With an average annual rainfall of around 1600 mm, EESGT is somewhat wetter than the Cerrado average of 1300 mm (Silva et al., 2005). The area is dominated by nutrient-poor, deep arenaceous quartz soils and has a high biodiversity. All the major Cerrado vegetation types are represented in the ecological station, but the area is dominated by open grasslands (capo limpo and campo sujo) and open savanna vegetation (cerrado ralo and cerrado típico/sensu strictu).

The fire season in EESGT lasts from about May until October and peaks around September (Fig. 2a). In the EDS managers apply fires during a 'safe-burning window' which depends on the vegetation type, vegetation conditions, and weather. Typically, EDS prescribed fire is applied in the afternoon and fires seize as temperature and wind speed drop and relative humidity increases after sunset. If the fires get too intense in the LDS, managers will actively repress fires to protect vulnerable vegetation and surrounding communities.

2.2 Measurement campaigns

We carried out one EDS- and two LDS campaigns. During the 2017 LDS (23 Sept - 11 Oct), fires were ignited between 9:30 and 18:00 and air temperature ranged from 25-38°C. No relative humidity measurements were taken during this campaign. In the EDS of 2018 (16-30 June), fires were ignited between 12:00 and 18:00. The air temperature during this period was between 31 and 36 °C with an average relative humidity of 18%. During the 2018 LDS (23 Sept - 11 Oct) samples were collected both

https://doi.org/10.5194/bg-2020-86
Preprint. Discussion started: 20 April 2020

in prescribed and non-prescribed fires, as we sampled smoke from gallery forest and humid grasslands during a fire repelling effort in the LDS. Although the LDS campaign in 2018 was after the first rainfall of the season, which came early in 2018, fire intensities appeared much higher than during the EDS campaign (Fig. 3). The temperatures ranged from 37-42 °C with an average relative humidity of 13%. More information about the number of measurements taken, and vegetation types burned during each campaign is listed in Table 1.

2.3 Sampling strategy

We filled single-polypropylene fitted Tedlar bags (SKC, type 232-01) with fresh smoke using a UAV-based (DJI, Matrice 100) sampling system. Most of the samples were taken 15-20 meters above the fire, with the height increasing with intensity of the fire. Our sampling system consisted of a container mounted on top of the drone which contained four Tedlar sample bags. We filled 1-liter bags with ±0.7 liters of smoke, which took 35 seconds for each bag creating a 35s-averaged mixture of trace gases in the bag. The sample inlet was located on the top of the UAV and fitted with a 60-µm sintered porous metal filter. During the sampling period, the system logged time, GPS coordinates, pressure, temperature and relative humidity on the UAV.

Most of the fires we sampled were ignited by the EESGT rangers using a drip-torch to start a fire line of at least 30 meters. We started sampling as soon as the vegetation directly ignited by the drip-torch seized to burn and the fire-front advanced 10-20 meters. We positioned the drone to capture a mixture of the fast-ascending flaming combustion products and the smouldering products that were generated upwind from the flaming fire-front. While the majority of the fires sampled were prescribed burns, we also sampled several non-prescribed fires. These fires were most likely escaped pasture fires or poaching fires, given that lightning did not occur during our LDS campaign. We sampled both EDS and LDS fires over various vegetation types with fire return times between 2 and 5 years (Table 1).

2.4 Smoke analysis

We used cavity ring-down spectroscopy to analyze CO_2, CO, CH_4, and N_2O concentrations from the sample bags. After sampling, the Tedlar bags were kept in a dark environment and analyzed within 12 hours. This was done in order to minimize the oxidation of CO by OH radicals inside the bags. According to Meyer et al. (2012) and our own tests, CO_2, CO, N_2O, and CH_4 concentrations are stable in the Tedlar bags for extended periods under these conditions. The samples were measured for 20 seconds using a CO_2 and CH_4 analyzer (Los Gatos Research, Microportable) followed by 20 seconds using a CO and N_2O analyzer (Aeris Technologies, Pico series), see Table 2. Measurement of the trace gas concentration in the bags was based on the 10s average concentration following a 10s initial flushing period. Before each fire, we filled four "background" samples at 10-20 meter altitude. The average concentration of these background samples was subtracted from those in the plumes to get the excess mixing ratio (EMR) in the sample bags. Variability between the background samples during a single day was smaller than 5%. Both analyzers were calibrated before and after each campaign using certified standard calibration gas (Table 2). No significant calibration drift was observed after the campaigns.

2.5 EF calculation

We converted the excess mixing ratio (EMR, sample minus background concentration) in the bags to EFs. The EFs for CO_2, CO, and CH_4 in grams of emitted species per kilogram of dry matter burned were calculated based on the carbon mass balance method (Urbanski, 2013; Yokelson et al., 1999):

$$EF_i = F_c \times \frac{MW_i}{AM_c} \times \frac{C_i}{C_{total}} \times 1000\ g\ kg^{-1} \quad (1)$$

Where EF_i is the emission factor of species i and Fc is the carbon content of the fuel by weight fraction. In this study, 48%, 50%, and 56% was used for grassland/savanna, gallery forest and humid grasslands respectively, based on carbon content measurements from different cerrado vegetation types by Susott et al. (1996). MW_i is the molecular mass of species i divided by the atomic mass of carbon (AM_c). C_i is the number of moles of carbon emitted in species i, C_{total} is the total number of moles of emitted carbon. Because we did not measure non-methane hydrocarbons (NMHC) and carbonaceous particulates (CPM), these fractions were estimated based on literature values. The total mass of emitted CPM was estimated to be 9.7% of the emitted mass of CO, with carbon accounting for 48% of the CPM-mass. The total amount of carbon in NMHC was estimated to be 3.5 times the $ER_{(CH4/CO2)}$ based on common ratios for savanna fires (Andreae, 2019; Yokelson et al., 2011, 2013). We did not consider residual ash in our calculations which can represent significant amounts of carbon (Jones et al., 2019). Although this is common practice in EF calculations, leaving out ash may lead to overestimation of carbon emissions (Surawski et al., 2016). To calculate the EFs for N_2O, we used Eq. (2) described by Andreae and Merlet (2001). This method uses the emission ratio ($ER_{(i/y)}$) of the species i to a relatively inert, co-emitted carbon-containing species y.

$$EF_i = ER_{(i/y)} \times \frac{MW_i}{MW_y} \times EF_y \quad (2)$$

We used CO_2 as the co-emitted reference gas. Although also CO is often used for this purpose due to its low background variability (Meyer et al., 2012), based on previous continuous emission measurements, we found N_2O to be more closely correlated with CO_2, conforming earlier work (Hao et al., 1991; Hurst et al., 1994; Surawski et al., 2015). The use of CO_2 or CO as a co-emitted reference gas for the N_2O EF calculations did not have a significant effect on the calculated emission factors (<0.01%). EFs were calculated for each bag separately, and we partitioned the bags into different season-, vegetation type-, and fire history classes. To calculate the weighted average EF for the classes, we calculated EFs over the cumulative EMR of the respective trace gas species in all the class' samples. Samples with low overall trace gas concentrations thus have low impact on the weighted average EF.

https://doi.org/10.5194/bg-2020-86
Preprint. Discussion started: 20 April 2020

To assess the seasonal effect of the combined emissions on radiative forcing (RF), we calculated the CO_2-eq EF based on the EFs weighted by the 100-year Global Warming Potentials (GWP_{100}). CH_4 and N_2O have a GWP_{100} of 34 and 298, respectively, when climate-carbon feedback mechanisms are included (Myhre et al., 2013). CO is usually not included but since it leads to a longer lifetime of CH_4, is a precursor for O_3, and eventually oxidizes to CO_2, we have also taken CO into account. Estimates of the CO GWP_{100} vary from 1.8 (Fry et al., 2012) to 5.4 when taking into account primary and secondary aerosol effects (Shindell and Faluvegi, 2009). We used a GWP_{100} for CO of 2.2 which is on the conservative side of these estimates. For CO and CH_4, the GWP includes the radiative forcing of the produced CO_2 once oxidized. To compensate for the sequestration of atmospheric CO_2 upon regrowth, we subtracted the global warming potential of CO_2 (1) from the GWP_{100} of all carbon-containing species.

2.6 Spatial analysis

All samples were geolocated using the coordinates of the UAV. This location was used to tag the samples with vegetation type and the number of years since the previous fire based on satellite data. Most of the plumes were sampled close to the fire, but we manually checked this information with satellite BA data to avoid mismatches due to plume advection. To calculate the fire history of the burned vegetation we used 30m Landsat thematic mapper (TM), enhanced thematic mapper (ETM) and operational land imager based BA data from the Instituto Nacional de Pesquisas Especiais (INPE) (Melchiori et al., 2015). The dataset uses consecutive Landsat scenes to detect changes in Normalized Difference Vegetation Index (dNDVI) and Normalized Burn Ratio (dNBR) for BA classification. The BA classification is manually validated in the field and thresholds in the algorithm were optimized for EESGT as described by Baradas et al. (2018). The number of years since the last fire was determined based on the location of the sample and the Landsat 30m burn-scars of the last years.

For vegetation classification, we used maps created by the University of Brasilia, which were derived from 5m RapidEye multispectral imagery (Carlos and Filho, 2017). The classification is based on spectral characterization of the different vegetation types and distinguishes the following cerrado classes: Campo limpo/sujo (0-5% tree cover), cerrado sensu stricto ralo (5-20%), cerrado sensu strictu típico (20-50%), and cerrado denso (>50%). The classification matched well with our field observations during the campaigns but we did not validate the map formally. It should be noted that the fractional tree cover (FTC) classification in the RapidEye map generally leads to higher FTC values compared to the Moderate Resolution Imaging Spectroradiometer (MODIS) based vegetation continuous fields dataset (MCD44Bv6, Townshend et al., 2011) or the Landsat-based rescaling of the MCD44Bv6 dataset (Sexton et al., 2013). Hence, care should be taken with spatial extrapolation of these vegetation classes using different FTC products.

https://doi.org/10.5194/bg-2020-86
Preprint. Discussion started: 20 April 2020

3. Results

The weighted average EFs for the different vegetation types, as well as the $\overline{EF}$ for combined cerrado vegetation are listed in Table 3. This weighting was based on burned area. Since the introduction of prescribed LDS burning in EESGT in the year 2014, the proportion of BA before the first of July has gradually increased (Fig. 2b). This has been the case for all dominant fire-prone vegetation types found in the protected area. As the samples were unevenly distributed over the different vegetation types (Table 1), we had to account for the sample bias in vegetation type to compare EDS and LDS EFs, our main objective. To obtain a seasonal weighted-average emission factor ($\overline{EF}$) for cerrado vegetation, we therefore weighed the different cerrado vegetation class EFs by their contribution to the fires in EESGT. Over the 2013-2018 timeframe, the distribution of the BA over the different cerrado vegetation types was approximately 23% open grassland, 42% open cerrado, 28% typical cerrado, and 7% dense cerrado (cerrado with over 50% tree cover). Since we lack data on the fuel load and combustion completeness we weighed the EFs by the percentage of the BA in the different classes (Fig. 4). Given that we do not have measurements of dense cerrado EFs, the dense cerrado BA was accounted for as typical cerrado. As the composition of EDS fires primarily depends on management considerations, both seasons were weighed by the total averaged BA composition.

3.1 Seasonality

Although the variability within individual fires (we collected several samples of each fire), vegetation types and campaigns were high, the difference between the season-averaged CO and CH_4 EFs was limited (Fig. 5). The MCE increased slightly from a weighted average of 0.972 in the EDS to 0.976 in the LDS. When zooming in on individual vegetation types, more efficient combustion in the LDS campaigns becomes apparent. For example, the difference between the LDS and EDS when averaged over all vegetation types (-15% for CO and -13% for CH_4) is more pronounced when focusing on more shrub-dominated area. For example, CO and CH_4 EFs were 18 and 21% lower in the LDS for typical cerrado vegetation (Table 3). As a result of the large spread in EFs and a limited number of samples in some vegetation types, only some differences were statistically significant.

Season-averaged N_2O EFs were 0.105 g kg^{-1} in the EDS and 0.123 g kg^{-1} in the LDS. However, internal variability within the campaigns was high with standard deviations of 0.183 g kg^{-1} in the EDS and 0.263 g kg^{-1} in the LDS. In Figs. 5-7 The green diamond represents the arithmetic mean and the red cross represents the EMR-weighted mean. Measurements more than 1.5 times the interquartile range (IQR) above the upper or below the lower quartile are presented as outliers (open circles). Whiskers represent the outermost values within 1.5 times the IQR of the respective quartiles. The third boxplot represents the spread in EFs from different studies on BB EF in savannas, and the value that is currently used in large scale emission assessments. If we investigate the N_2O EF seasonality within the vegetation type classes, we find opposite trends (Table 3). In the campo limpo/campo sujo grasslands, the weighted average N_2O EF in the EDS was more than double the N_2O EF in the

LDS. In the shrub-dominated cerrado ralo and cerrado tipico, however, the weighted-average N_2O EFs were 22% and 54% higher in the LDS.

3.2 EF variability over vegetation type and fire history

We found no significant differences in CO EF and CH_4 EF between the EMR-averaged values of the different cerrado vegetation types, despite substantial differences in tree cover density (Fig 6). The samples we took over gallery forest contained much higher EFs for CO and CH_4, indicating more smouldering combustion. The N_2O EF was found to be positively correlated with tree cover and was a factor 5 higher in the gallery forest compared to savanna vegetation.
Fire-frequency had some effect on the burning efficiency. We found a decrease in the CO EF and CH_4 EF with increasing time between fires ranging from 2 to 4 years in samples from the open grasslands (Fig. 7). Although the measurements in typical cerrado did not cover the entire fire-frequency span, the available data suggested no significant relation between EFs and the years since the last fire in both open cerrado- and typical cerrado vegetation (not shown).

3.3 GWP variability between EDS and LDS fire

Fig. 8 shows the cumulative CO_2–equivalent (eq) of the respective gases, based on a 100-year time span. Overall, CO_2-eq emissions per kg of dry fuel in the Cerrado were 5.3% lower in the LDS compared to the EDS. The difference between EDS and LDS CO_2-eq can largely be contributed to somewhat more efficient combustion in the LDS which is partially compensated for by a higher N_2O EF. The black error bar represents the prorogation of the N_2O emission uncertainty range to the net CO_2-eq emissions. The bar illustrates that differences in N_2O EFs were small compared to the measurement uncertainty. Even without taking aerosol effects into account, the indirect radiative forcing due to CO made up a significant portion (32-53%) of total CO_2-eq emissions.

4. Discussion

4.1 Difference in EFs between EDS vs LDS fires

Korontzi et al. (2003) found that seasonality affected MCE in prescribed burn plots in southern African savannas. This would limit or even cancel climate benefits of EDS prescribed burning. They found that for 'Dambo' grasslands, EFs for reduced species were strongly correlated with the percentage of green grass in the fuel. This percentage decreases as grasses cure over the course of the dry season. Using satellite-derived NDVI, Korontzi (2005) used this relation to find a seasonal trend of increasing MCE over the dry season in the southern African savannas. A similar trend was found by Yokelson et al. (2011) when comparing EF measurements for EDS fires in Mexico to LDS African savanna measurements. Direct measurements taken during the West Arnhem Land Fire Abatement Project (WALFA) in northern Australia, however, showed no significant seasonal fluctuation in both CH_4 and N_2O EFs (Meyer et al., 2012). Measurements taken in Zambian miombo woodlands did not show significant seasonal MCE fluctuation either (Hoffa et al., 1999).

https://doi.org/10.5194/bg-2020-86
Preprint. Discussion started: 20 April 2020

In this study we measured EFs during low-intensity fires in the EDS as well as higher intensity LDS fires in the same region. Although we also found some seasonal dependency, the decrease of for CO (-15%) and CH_4 (-13%) was small compared to the -70% found by Korontzi et al. (2003). In addition, seasonal variability was small compared to the variability within a EDS or LDS campaign. The average N_2O EF over the combined cerrado samples showed a slight increase over the season, though stronger and opposing seasonal trends were found in the individual vegetation classes. Meyer et al. (2012) also found opposing seasonal N_2O EF trends for different vegetation types. Although, the formation process of N_2O is often linked to combustion characteristics (Kilpinen and Hupa, 1991; Meyer et al., 2012; Winter et al., 1999a), we did not find a significant correlation of the N_2O EF with MCE. Overall, MCE values were higher than the average MCE values derived from CO_2 and CO EFs for savanna and grassland fires in Andreae (2019), but within the range of previous measurements from cerrado vegetation (Ferek et al., 1998; Ward et al., 1991). Over all cerrado vegetation types combined, the weighted average CH_4 EF slightly declined over the season.

We conducted the EDS experiments in June when the majority of the prescribed burning takes place (Fig. 2a). Although the LDS measurements in 2018 were taken after the first rains, conditions were still hotter and dryer than during the EDS, and the combustion completeness appeared to be higher (Fig. 3). Larger differences may be expected earlier in the dry season in the period March-May (Dri et al., 2018). During these months, when humidity is still very high, prescribed burning efforts focus on the protection of vulnerable ecosystems such as peatlands and gallery forests, as well as areas around homes and farmlands, but total BA is limited. Additional measurements in the very start of the dry season (March-May) should confirm whether the differences increase for these fires. Rissi et al. (2017) measured fuel characteristics, rate of spread, flame height, fire intensity (kW m^{-1}) and combustion completeness in campo sujo (<20% tree-cover) vegetation for prescribed burns in May, July and October. Although the spread in fire intensity between fires was higher later in the season, they found no significant differences between the July and August treatments. According to them fire intensity was best explained by fuel build-up; this is consistent with the MCE increase we found between 2-4 years of fuel build-up in campo sujo vegetation (Fig. 8). The finding that the number of years since the last burn did not significantly affect the combustion efficiency after 4 years is consistent with the results from Govender et al. (2006). However, we only found this correlation in open grassland with annual grasses leading to accumulation of easily combustible dead biomass.

4.6 Variability in CO and CH_4 EFs

According to our results, there was no significant difference in CO and CH_4 EFs between the dominant savanna vegetation types in EESGT: campo limpo/sujo, cerrado ralo, and cerado tipico. Overall, the weighted average CO and CH_4 EFs for these combined savanna fuel types were lower than most of the existing literature on savanna fires (Akagi et al., 2011; Andreae, 2019). This is shown in Fig. 9 where the individual CH_4 EF measurements are plotted as as a function of MCE measured for the cerrado vegetation types. Results from other studies, plotted as the study-averages, are shown based on the individual papers included in Andreae (2019). The averaged EFs were rather similar between EDS and LDS campaigns, but within each

https://doi.org/10.5194/bg-2020-86
Preprint. Discussion started: 20 April 2020

campaign, the EFs varied substantially. The shift in the LDS towards a steeper slope of the CH_4 EF/MCE linear regression in Fig. 9 may be an indication of a shift toward more woody fuels (Van Leeuwen and Van der Werf, 2011). Although the lower CH_4 EF found in this study can partially be explained by on average higher MCE values in our plots, the CH_4 EFs were much lower than average CH_4 EFs of savanna literature studies with the same MCE. Within the total range of variability, the slopes of the linear regression we found for both EDS and LDS campaigns were significantly less steep compared to the regression slope based on previous measurements of savanna vegetation CH_4 EFs. Part of this comes from a larger number of earlier work in the 0.90-0.95 MCE; in the higher MCE ranges our results deviate less from earlier work. This may indicate that there is more variability in fire processes between different savanna than often thought.

The difference between EDS and LDS weighted average CH_4 EF is partly the result of a higher spread and high-concentration RSC samples in the LDS (Fig. 10). Although the CH_4 EF was lower in the LDS (-13%, Table 3), the overall spread of CH_4 EFs in the LDS fires was higher than during EDS fires. Moreover, during the EDS, high CH_4 EFs are mostly found in samples with low overall trace gas concentrations, meaning their impact on the EMR-weighted average was small.

An explanation for the increased spread of CH_4 EFs in the LDS may be the effects of a more complete combustion of grasses and fine fuels on one hand, and an increased share of RSC-prone fuels like woody materials in the fuel mixture leading to a higher CH_4 EF on the other hand (Bertschi et al., 2003, Hoffa et al., 1999). These fuels typically contain more moisture and are densely packed. Therefore, they are more likely to burn in the LDS when humidity is low (Akagi et al., 2011; Eck et al., 2013; van Leeuwen et al., 2014). This was also observed in Australian savannas, were combustion completeness of woody debris was found to be twice as high in the LDS compared to EDS fires (Yates et al., 2015).

Savanna areas with higher vegetation densities had slightly higher EFs for N_2O. Furthermore, there was an opposite seasonal trend in N_2O EFs from grass-dominated campo limp/campo sujo (-61% from EDS to LDS) and shrub-dominated cerrado ralo (+22%) and cerrado tipico (+54%). Winter et al. (1999b) found N_2O EFs to be closely correlated to the nitrogen content of the fuel but we did not measure this. Susott et al. (1996) and Ward et al. (1992) measured the dry-weight carbon and nitrogen contents of various fractions of savanna fuels. For the cerrado, they analysed dead- and living grass, dicots, litter, leaves and various woody debris fractions for the most fire-prone cerrado classes studied in this paper. While carbon-content in living grasses was only slightly higher compared to dead grasses, nitrogen content in living grass was on average more than twice that of dead grass. They also found that nitrogen contents of leaf, litter and dicot fractions increased in more woody vegetation types. The nitrogen content of coarse woody debris tends to decrease with the size of the debris. The opposite seasonal trends in N_2O EFs may therefore be related to a seasonal shift in vegetation type that burns. Many shrubs and trees in EESGT are deciduous or semi-deciduous and drop all or part of their leaves throughout the dry season. This creates a fire-prone, nitrogen-rich litter layer that burns in the LDS fires. In the open grasslands, where leaf litter is not as significant to the fuel mixture, the ratio of dead versus living grasses increases which could reduce the nitrogen content of the fuel (Yokelson et al., 2011).

https://doi.org/10.5194/bg-2020-86
Preprint. Discussion started: 20 April 2020

Whether this is indeed the explanation for the opposite seasonal trends in N_2O emission factors requires future campaigns to include measurements of fuel load, combustion completeness, and nitrogen content over the whole season.

During the LDS, fires can escape into the peatlands and gallery forests lining the rivers. Many EF measurements in the savanna biome are conducted in research plots that are representative of the typical savanna vegetation. These plots, therefore, do not include EFs of these fine-scale features. For this reason, we assess them separate, and do not include them in the cerrado weighted averages. Fires will only occur in these regions in the LDS, when the vegetation is dry and the groundwater table low. As these are not fire-prone vegetation types, regular burning is not necessary for sustaining biodiversity. Although these areas are small, fires can persist for several consecutive days and vegetation recovery of the carbon stocks is a much slower process. Late wet season fires registered in vulnerable vegetation types are typically management fires which, under the right conditions, burn away moribund fuels. Because we only took a few samples from gallery forests (26 samples) and humid grassland (15 samples), more research is needed in these vegetation types. Based on the current measurements and relatively high N:C ratio of these ecosystems as described in literature, the N_2O EF of 0.2 g kg^{-1}, currently being used by emission databases for both "savanna" and "tropical forest" seems to underestimate N_2O emissions for the gallery forest in the EESGT. The CH_4 EFs for humid grasslands and gallery forests are consistent with EFs for tropical peat (Hu et al., 2018; Smith et al., 2018) and tropical forests (Akagi et al., 2011) respectively.

4.2 Uncertainties

The main uncertainties associated with calculating fire-averaged EFs from field measurements include representativeness of the measurements taken related to the sampling strategy, measurement uncertainties, and assumptions based on other literature to represent factors not measured but required to compute EFs.

4.2.1 Sampling strategy

Given the unpredictable nature of fires and difficulties to move around during a spreading fire in a protected area without many roads, we tackled each fire differently. We could not standardize the strategy to sample head-, back-, and sideway propagating fires. Especially in the LDS fires, it was difficult to take many samples over the fast-moving fire front. Therefore, sideway propagating fires may be overrepresented in the dataset. According to Surawski et al. (2015) based on wind tunnel experiments and Wooster et al., (2011) based on experimental field burns, fire spread mode affects the EFs with, in general, lower MCE in headfires. Compared to earlier studies, we have taken a much larger number of samples thus lowering biases. To better calculate the representative mean requires better-contained fires that are easier to access and continuous sampling at various locations. Since every fire is different it might be difficult to fully understand the correct sampling strategy and weighting approach.

During the LDS, fires were predominantly sampled from 11:00 until 16:00 when temperatures are highest. However, these LDS fires generally last for multiple days, and measurements during the night and early morning are under-represented in the

https://doi.org/10.5194/bg-2020-86
Preprint. Discussion started: 20 April 2020

dataset. Diurnal fluctuations in temperature, wind, and humidity may cause these fires to behave more similar to EDS fires during these times. Even though the amount of carbon consumed during those times is lower than during the day, future efforts could shed light on the diurnal cycle of EFs.

An additional source of uncertainty stems from a potential bias related to the time of sampling. During RSC, EMRs were low and contributed little to the weighted average. If the sampling period overlapped with the fire duration, as was often the case for grasslands, this would be a representative number. However, as RSC may persist also after we stopped sampling, EFs of predominantly RSC products such as CO and CH_4 may be slightly underestimated using our sampling strategy. In Fig. 4 the difference between the arithmetic mean (green triangle) and the weighted mean (red square) represents the effect of weighing the bags by excess mixing ratio. In most cases, the difference is small, suggesting that the total contribution of RSC is limited. This is consistent with Ward et al. (1992), who measured BB emissions in cerrado vegetation. They found that over 97% of the total carbon released was emitted during the flaming phase. The relatively low significance of RSC in grass-dominated savannas was also found for experiments in the Kruger national park, South Africa (Cofer et al., 1996; Wooster et al., 2011). While the role of RSC in these grass-dominated ecosystems is thus thought to be small, the significance of RSC in areas with more woody fuel may be higher (Bertschi et al., 2003; Christian et al., 2007; Hao et al., 1991). With prescribed fire-management, dead organic matter and woody carbon stocks may increase over time (Oliveras et al., 2013; Pivello, 2011; Veenendaal et al., 2018). For long-term emission abatement potential, it is therefore important to understand how these changes in fuel composition affect EFs.

4.2.2. EF calculations and assumptions

Ideally, EF calculations are based on measurements of all carbon-containing species that are emitted. This allows for the direct conversion of emission ratios to EFs per unit of burned fuel. We did not measure non-methane hydrocarbons (NMHC) and carbonaceous particulates (CPM). When combined, these can account for a significant portion of the total carbon emitted. To account for this, we have made assumptions for the C_{NMHC}/C_{CH4} ratio (3.5, R.J. Yokelson, personal correspondence), the $PM_{2.5}$/CO mass ratio (0.097) and the carbon fraction of $PM_{2.5}$ (0.70), based on Andreae (2019) and Reid et al. (2005). This adds an additional 0.4-2.7% C from NMHC and 0.5-1.9% C from CPM to the total carbon balance. Most studies only include carbonaceous trace gases in the total carbon. However, leaving out part of the carbonaceous emissions artificially increases the EFs of the measured species. This inflation is proportional to the carbon that is not accounted for and will likely be in the 1-5% range (Akagi et al., 2011; Yokelson et al., 2013). EFs for both NMHC and PM are negatively correlated with combustion efficiency (Hoffa et al., 1999; Yokelson et al., 2013). Therefore, the overestimation of EF would be slightly larger in the EDS compared to the LDS. As the N_2O EF is coupled to a carbonaceous co-emitted species, in our case CO_2, this inflation will also affect the N_2O EF.

Another source of uncertainty is the carbon content of the fuel. EFs scale linearly with this fraction and we used 48% for cerrado vegetation, 50% for gallery forests, and 56% for humid grasslands. Had we made other assumptions, for example 45% (Andreae, 2019; Andreae and Merlet, 2001) or 50% (Akagi et al., 2011; Urbanski, 2014), our EF estimates would have been 4% lower to 6% higher in the typical cerrado types, 10% lower or equal in gallery forest, and 12-22% higher for humid grasslands. This scaling does not affect the spatial and temporal patterns we found.

4.2.2. CO_2-eq calculations and assumptions

Finding a useful metric to assess the direct and indirect impact on RF and climate is challenging, as mechanisms and time frames differ (Fuglestvedt et al., 2010). Atmospheric impact may depend on geographic location, injection height or atmospheric conditions (Fry et al., 2012). We used a GWP_{100} for CO of 2.2, not considering primary and secondary aerosol effects. Including these effects would increase the effect of CO by 50% for only primary, and 140% for primary and secondary aerosol effects (Shindell and Faluvegi, 2009). Due to the short (2-3 months) atmospheric lifetime of CO, using the short term GWP_{20} would lead to a ±3 times higher impact (Myhre et al., 2013).

In the savanna biome, fires typically occur frequently with fire return times depending, amongst others, on the amount of rainfall. Higher rainfall in general supports higher fire frequencies. As the vegetation recovers after a fire, atmospheric CO_2 is captured during photosynthesis, thus balancing CO_2 emissions during the fire. This net-zero emission for CO_2 is true for the savanna species with rapid regrowth while forest CO_2 emissions from fires take longer to be compensated for. For peat underlying humid grasslands, however, some of these emissions can be attributed to carbon that was stored over thousands of years. These carbon stocks will not regenerate at a rate that is relevant to current climate change. As peat layers are still moist in the EDS, the ratio of aboveground fuel with a short carbon cycle to long carbon-cycle peat may be seasonally dependent. Also, in the case of deforestation, CO_2 uptake does not balance out the loss in biosphere carbon stocks due to the fire. If we do not assume CO_2 uptake, CO_2-eq EFs would be 577% and 402% higher for gallery forest and peat, respectively. Our assumptions to calculate the climate impact of fires should therefore be seen as conservative.

4.4. N_2O EF uncertainty

N_2O EFs were significantly lower than the 0.20 g kg^{-1} that is currently used in GFED based on Akagi et al. (2011) and the 0.21 g kg^{-1} for savanna in Andreae and Merlet (2001). However, the values we find are more in line with other savanna measurements from South-American (0.05-0.07 g kg^{-1}; Hao et al., 1991; Susott et al., 1996), Australia (0.07 – 0.12 g kg^{-1}; Hurst et al., 1994; Meyer et al., 2012; Surawski et al., 2015) and Africa (0.16 g kg^{-1}; Cofer et al., 1996). The high average N_2O EF in these EF databases may partially be linked to the use of stainless steel sample containers in older studies, leading to N_2O formation in the sample container (Muzio and Kramlich, 1988). Due to the low concentrations and small departure from background conditions, N_2O is a notoriously difficult measurement. Fig. 10 shows that many EFs were negative. This occurs

https://doi.org/10.5194/bg-2020-86
Preprint. Discussion started: 20 April 2020

when concentrations in the smoke samples were below background concentrations. Although N_2O is destroyed in flaming combustion (Winter et al., 1999a, 1999b) and negative emissions are thus theoretically possible, we expect it is more likely to be a measurement error. We found extremely high and low EFs mostly at low overall excess mixing ratios for both CO_2 and CO. The normal Gaussian distribution pattern in Fig. 11 indicates high measurement uncertainty at low smoke concentrations. The positive and negative tails of this Gaussian error partially balance out and their weight is low relative to higher concentration measurements. Therefore, the effects of this error on the weighted average EFs should be limited. Still, a degree of caution is advised while dealing with N_2O EFs. The relative error in the 2017 campaign was higher than in the 2018 campaigns; this is because improvements in software after 2017. When comparing the same dataset based on vegetation type, a clear shift of the average N_2O EF can be found (Fig. 11b). For vegetation types with a low number of measurements or cumulative smoke signal, the large spread means a much higher uncertainty.

4.5 Limitations of the study

The findings of this study have to be seen in light of some limitations. Field measurements take place in an uncontrolled environment. This means wind conditions vary, possibly affecting the temperature and combustion efficiency of the fire and the type of fuel it consumes. Many processes happen at once during a fire making it challenging to obtain a representative EF for all stages of the process. Future research will focus on further improving the UAV-based measurement methodology to avoid possible biases discussed in Sect. 4.2.1. We used generalized vegetation classes based on remote sensing data. However, we lacked fuel measurements to substantiate or nuance this classification. Although we took many samples, the sample size for individual categories of 'vegetation class' and 'years without fire' is in some cases small, meaning we could not always disentangle all different combinations of classes. Measuring more fires, covering a larger geographical area, and adding fuel- and wind speed measurements could provide further insights for the variability we found.

5. Conclusions

We obtained over 800 fresh smoke samples in different cerrado vegetation types, during three fieldwork campaigns at various stages of the fire season. EFs of CO_2, CO, CH_4, and N_2O were calculated from the difference between sample bag and background concentrations based on the carbon mass balance method. While we found some evidence pointing towards more efficient combustion in the LDS, variability in EFs over the season was in general low. This finding is based on averaging a large number of samples; variability during each campaign was substantial and partly related to vegetation type and fire history in open grasslands, while relative humidity only had a minor impact on variability. Our findings thus imply that the effectiveness of carbon mitigation in fire abatement programs is not impacted significantly by seasonal changes in EFs for the fieldwork site and length of fire season sampled.

Overall, EFs for CO and CH_4 were 36% and 72% lower than EFs found in previous studies in the Cerrado and savanna fires in general. The lower CH_4 EFs compared to previous studies were not fully explained by a higher MCE, but rather by a reduction in the steepness of the slope of the linear regression of CH_4 EF as a function of MCE. We found that in our study region, N_2O EFs for cerrado vegetation were approximately half the value used in large-scale emission assessments. Uncertainties for N_2O measurements are high, especially in low-concentration samples. However, these lower EFs are also found in more recent savanna studies and could indicate a substantial overestimation of the contribution of fires in the N_2O budget in global databases. Seasonal effects in the N_2O EF were opposite for grass fuels contrasted to more shrub-dominated vegetation types. Finally, our findings indicate that CO should be considered in carbon schemes. While not a greenhouse gas, through its indirect effect on the OH concentration it has a significant effect on fire radiative forcing.

Data availability

Measurement data is available upon request.

Author's contribution

RV, GRvdW, and MVGA designed the study; RV and MBA conducted the experiments; RV, MMC and GRvdW participated in data analysis and/ or interpretation; RV wrote the manuscript; RV, GRvdW, ACSB edited the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

Acknowledgements

This research has been supported by the Nether- lands organization for Scientific Research (NWO) (Vici scheme research programme, no. 016.160.324). The Chico Mendes Institute for Conservation of Biodiversity (ICMbio) and the Center for Environmental Monitoring and Fire Management (CEMAF) led the fieldwork which would not have been possible without the rangers working at EESGT. Also, Alan Silva, Eduardo Ganassoli Neto, Micael Moreira, and Jader Nunes Cachoeira were indispensable for providing all logistics related to the fieldwork. We thank Robert Yokelson and Martin Wooster for valuable discussions on emission factor calculation. Finally, we wish to thank Anja Hoffmann for connecting the authors.

References

Abreu, R. C. R., Hoffmann, W. A., Vasconcelos, H. L., Pilon, N. A., Rossatto, D. R. and Durigan, G.: The biodiversity cost of carbon sequestration in tropical savanna, Sci. Adv., 3(August), 1–8, doi:10.1126/sciadv.1701284, 2017.

Akagi, S. K., Yokelson, R. J., Wiedinmyer, C., Alvarado, M. J., Reid, J. S., Karl, T., Crounse, J. D. and Wennberg, P. O.: Emission factors for open and domestic biomass burning for use in atmospheric models, Atmos. Chem. Phys., 11(9), 4039–4072, doi:10.5194/acp-11-4039-2011, 2011.

Anderson, R., Beatty, R., Russell-Smith, J. and van der Werf, G. R.: The global potential of indigenous fire management: findings of the regional feasibility assessments., 2015.

Andreae, M. O.: Emission of trace gases and aerosols from biomass burning – an updated assessment, Atmos. Chem. Phys., 19, 8523–8546, doi:10.5194/acp-19-8523-2019, 2019.

Andreae, M. O. and Merlet, P.: Emission of trace gases and aerosols from biomass burning, Biogeochemistry, 15(4), 955–966, doi:10.1029/2000GB001382, 2001.

Baradas, A. C. S., Borges, M. A. and Costa, M. M.: Plano de manejo integrado do fogo - Estação Ecológica Serra Geral do Tocantins, Rio da Conceição., 2018.

Beringer, J., Hutley, L. B., Tapper, N. J. and Cernusak, L. A.: Savanna fires and their impact on net ecosystem productivity in North Australia, Glob. Chang. Biol., 13(5), 990–1004, doi:10.1111/j.1365-2486.2007.01334.x, 2007.

Bertschi, I., Yokelson, R. J., Ward, D. E., Babbitt, R. E., Susott, R. A., Goode, J. G. and Hao, W. M.: Trace gas and particle emissions from fires in large diameter and belowground biomass fuels, J. Geophys. Res. Atmos., 108(D13), n/a-n/a, doi:10.1029/2002JD002100, 2003.

Carlos, J. and Filho, O.: Avaliação do Uso da Abordagem Orientada-Objeto com Imagens de Alta Resolução RapidEye na Classificação das Fitofisionomias do Cerrado Juan, 2017.

Chen, L. A., Verburg, P., Shackelford, A., Zhu, D., Susfalk, R., Chow, J. C. and Watson, J. G.: and Physics Moisture effects on carbon and nitrogen emission from burning of wildland biomass, Atmos. Chem. Phys., 10, 6617–6625, doi:10.5194/acp-10-6617-2010, 2010.

Christian, T. J., Yokelson, R. J., Jr, A. C., Griffith, D. W. T., Alvarado, E. C., Santos, C., Gomes, T., Neto, S., Veras, C. A. G. and Hao, W. M.: The tropical forest and fire emissions experiment : Trace gases emitted by smoldering logs and dung from deforestation and pasture fires in Brazil, J. Geophys. Res., 112, 1–14, doi:10.1029/2006JD008147, 2007.

Cofer, W. R., Levine, J. S., Winstead, E. L., Cahoon, D. R., Sebacher, D. I., Pinto, P. and Stocks, B. J.: Source compositions of trace gases released during African savanna fires, J. Geophys. Res., 101, 23,597-23,602, 1996.

Cook, G. D., Liedloff, A. C. and Murphy, B. P.: Towards a methodology for increased carbon sequestration in dead fuels through implementation of less severe fire regimes in savannas, in Carbon Accounting and Savanna Fire Management, edited by B. P. Murphy, A. C. Edwards, M. Meyer, and J. Russell-smith, pp. 321–326, CSIRO Publishing, Clayton South., 2015.

Crutzen, P. J. and Zimmermann, P. H.: The changing photochemistry of the troposphere, Tellus, 43AB, 136–151, doi:10.1034/j.1600-0870.1991.00012.x, 1991.

Dri, A. B. N., Soro, T. D., Gignoux, J., Dosso, K., Koné, M., Dri, J. K. N., Koné, N. A. and Barot, S.: Season affects fire behavior in annually burned humid savanna of West Africa, Fire Ecol., 14(5), doi:10.1186/s42408-018-0005-9, 2018.

Durigan, G., Ratter, J. A., State, P. and Box, P. O.: The need for a consistent fire policy for Cerrado conservation, J. Appl. Ecol., (Dias 2006), 11–15, doi:10.1111/1365-2664.12559, 2016.

Eck, T. F., Holben, B. N., Reid, J. S., Mukelabai, M. M., Piketh, S. J., Torres, O., Jethva, H. T., Hyer, E. J., Ward, D. E., Dubovik, O., Sinyuk, A., Schafer, J. S., Giles, D. M., Sorokin, M., Smirnov, A. and Slutsker, I.: A seasonal trend of single scattering albedo in southern African biomass-burning particles : Implications for satellite products and estimates of emissions for the world ' s largest biomass-burning source, J. Geophys. Res. Atmos., 118, 6414–6432, doi:10.1002/jgrd.50500, 2013.

https://doi.org/10.5194/bg-2020-86
Preprint. Discussion started: 20 April 2020

Ferek, R. J., Reid, J. S., Hobbs, P. V., Blake, D. R. and Liousse, C.: Emission factors of hydrocarbons , halocarbons , trace gases and particles from biomass burning in Brazil, J. Geophys. Res., 103(May 2014), doi:10.1029/98JD00692, 1998.

Fidelis, A. and Fernanda, M.: Above- and below-ground biomass and carbon dynamics in Brazilian Cerrado wet grasslands, J. Veg. Sci., 24, 356–364, doi:10.1111/j.1654-1103.2012.01465.x, 2013.

Fidelis, A., Alvarado, S., Barradas, A., Pivello, V., Fidelis, A., Alvarado, S. T., Barradas, A. C. S. and Pivello, V. R.: The Year 2017: Megafires and Management in the Cerrado, Fire 2018, Vol. 1, Page 49, 1(3), 49, doi:10.3390/FIRE1030049, 2018.

Fry, M. M., Naik, V., West, J. J., Schwarzkopf, M. D., Fiore, A. M., Collins, W. J., Dentener, F. J., Shindell, D. T., Atherton, C., Bergmann, D., Duncan, B. N., Hess, P., MacKenzie, I. A., Marmer, E., Schultz, M. G., Szopa, S., Wild, O. and Zeng, G.: The influence of ozone precursor emissions from four world regions on tropospheric composition and radiative climate forcing, J. Geophys. Res. Atmos., 117(7), 1–16, doi:10.1029/2011JD017134, 2012.

Fuglestvedt, J. S., Shine, K. P., Berntsen, T., Cook, J., Lee, D. S., Stenke, A., Skeie, R. B., Velders, G. J. M. and Waitz, I. A.: Transport impacts on atmosphere and climate: Metrics, Atmos. Environ., 44(37), 4648–4677, doi:10.1016/j.atmosenv.2009.04.044, 2010.

Giglio, L. and Justice, C. O.: MOD14A1 MODIS/Terra Thermal Anomalies/Fire Daily L3 Global 1km SIN Grid V006 [Data set], NASA EOSDIS L. Process. DAAC, doi:https://doi.org/10.5067/MODIS/MOD14A1.006, 2015.

Govender, N., Trollope, W. S. W. and Van Wilgen, B. W.: The effect of fire season, fire frequency, rainfall and management on fire intensity in savanna vegetation in South Africa, J. Appl. Ecol., 43(4), 748–758, doi:10.1111/j.1365-2664.2006.01184.x, 2006.

Hao, W. M., Scharffe, D., Lob, J. M. and Crutzen, P. J.: Emissions of N20 from the Burning of Biomass in an Experimental System, Geophys. Res. Lett., 18(6), 999–1002, 1991.

Hoffa, E. A., Ward, D. E., Hao, W. M., Susott, R. A. and Wakimoto, R. H.: Seasonality of carbon emissions from biomass burning in a Zambian savanna, J. Geophys. Res., 104, doi:10.1029/1999JD900091, 1999.

Hu, Y., Fernandez-Anez, N., Smith, T. E. L. and Rein, G.: Review of emissions from smouldering peat fires and their contribution to regional haze episodes, Int. J. Ofwildl. Fire 2018, 27, 293–312, 2018.

Hurst, D. F., Griffith, D. W. T., Carras, J. C., Williams, D. j. and Fraser, P. J.: Measurements of Trace Gases Emitted by Australian Savanna Fires During the 1990 Dry Season, J. Atmos. Chem., 18, 33–56, doi:10.1007/2FBF00694373, 1994.

Ito, A. and Penner, J. E.: Global estimates of biomass burning emissions based on satellite imagery for the year 2000, J. Geophys. Res. D Atmos., 109(14), 1–18, doi:10.1029/2003JD004423, 2004.

Jones, M. W., Santín, C., van der Werf, G. R. and Doerr, S. H.: Global fire emissions buffered by the production of pyrogenic carbon, Nat. Geosci., 12(9), 742–747, doi:10.1038/s41561-019-0403-x, 2019.

Kauffman, J. B., Cummings, D. L. and Ward, D. E.: Relationships of Fire , Biomass and Nutrient Dynamics along a Vegetation Gradient in the Brazilian Cerrado, J. Ecol., 82(3), 519–531, doi:10.2307/2261261, 1994.

Kilpinen, P. and Hupa, M.: Homogeneous N2O chemistry at fluidized bed combustion conditions: A kinetic modeling study, Combust. Flame, 85(1–2), 94–104, doi:10.1016/0010-2180(91)90179-F, 1991.

Klink, C. A. and Machado, R. B.: Conservation of the Brazilian Cerrado, Conserv. Biol., 19(3), 707–713, doi:10.1111/j.1523-1739.2005.00702.x, 2005.

Korontzi, S.: Seasonal patterns in biomass burning emissions from southern African vegetation fires for the year 2000, Glob. Chang. Biol., 11(10), 1680–1700, doi:10.1111/j.1365-2486.2005.001024.x, 2005.

Korontzi, S., Ward, D. E., Susott, R. A., Yokelson, R. J., Justice, C. O., Hobbs, P. V., Smithwick, E. A. H. and Hao, W. M.: Seasonal variation and ecosystem dependence of emission factors for selected trace gases and PM 2.5 for southern African savanna fires, J. Geophys. Res. Atmos., 108(D24), doi:10.1029/2003jd003730, 2003.

Landry, J. S. and Matthews, H. D.: Non-deforestation fire vs. fossil fuel combustion: The source of CO2 emissions affects the global carbon cycle and climate responses, Biogeosciences, 13(7), 2137–2149, doi:10.5194/bg-13-2137-2016, 2016.

van Leeuwen, T. T. and van der Werf, G. R.: Spatial and temporal variability in the ratio of trace gases emitted from biomass burning, Atmos. Chem. Phys., 11(8), 3611–3629, doi:10.5194/acp-11-3611-2011, 2011.

van Leeuwen, T. T., van der Werf, G. R., Hoffmann, A. A., Detmers, R. G., Rücker, G., French, N. H. F., Archibald, S., Carvalho, J. A., Cook, G. D., De Groot, W. J., Hély, C., Kasischke, E. S., Kloster, S., McCarty, J. L., Pettinari, M. L., Savadogo, P., Alvarado, E. C., Boschetti, L., Manuri, S., Meyer, C. P., Siegert, F., Trollope, L. A. and Trollope, W. S. W.: Biomass burning fuel consumption rates: A field measurement database, Biogeosciences, 11(24), 7305–7329, doi:10.5194/bg-11-7305-2014, 2014.

Lipsett-Moore, G. J., Wolff, N. H. and Game, E. T.: Emissions mitigation opportunities for savanna countries from early dry season fire management, Nat. Commun., 9(1), 1–8, doi:10.1038/s41467-018-04687-7, 2018.

Lobert, J. M. and Warnatz, J.: Emissions from the Combustion Process in Vegetation, Fire Environ. Its Ecol. Atmos. Clim. Importance, 15–38, 1993.

Maraseni, T. N., Smith, K. R., Griffiths, G. and Apan, A.: Savanna burning methodology for fire management and emissions reduction : a critical review of influencing factors, Carbon Balance Manag., doi:10.1186/s13021-016-0067-4, 2016.

Melchiori, A. E., Setzer, A. W., Morelli, F., Libonati, R., Cândido, P. D. A. and Jesús, S. C. De: A Landsat-TM / OLI algorithm for burned areas in the Brazilian Cerrado – preliminary results A Landsat-TM / OLI algorithm for burned areas in the Brazilian Cerrado – preliminary results, VII Int. Conf. For. Fire Res., (November 2014), doi:10.14195/978-989-26-0884-6, 2015.

Meyer, C. P., Cook, G. D., Reisen, F., Smith, T. E. L., Tattaris, M., Russell-Smith, J., Maier, S. W., Yates, C. P. and Wooster, M. J.: Direct measurements of the seasonality of emission factors from savanna fires in northern Australia, J. Geophys. Res. Atmos., 117(20), doi:10.1029/2012JD017671, 2012.

Miranda, H. S., Sato, M. N., Neto, W. N. and Aires, F. S.: Fires in the cerrado, the Brazilian savanna, in Tropical Fire Ecology, pp. 427–450, Springer Berlin Heidelberg, Berlin, Heidelberg., 2009.

Murphy, B. P., Russell-smith, J. and Prior, L. D.: Frequent fires reduce tree growth in northern Australian savannas : implications for tree demography and carbon sequestration, Glob. Chang. Biol., 16, 331–343, doi:10.1111/j.1365-2486.2009.01933.x, 2010.

Muzio, L. J. and Kramlich, J. C.: An artifact in the measurement of N2O from combustion sources, Geophys. Res. Lett., 15, 1369–1372, doi:https://doi.org/10.1029/GL015i012p01369, 1988.

Myhre, G., Shindell, D. T., Breon, F.-M., Collins, W. J., Fluglestvedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T. and Zhang, H.: Anthropogenic and Natural Radiative Forcing, in Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, vol. 6, p. 146, Cambridge University Press., 2013.

Oliveira, S. L. J., Campagnolo, M. L., Price, O. F., Edwards, A. C., Russell-smith, J. and Pereira, J. M. C.: Ecological implications of fine-scale fire patchiness and severity in tropical savannas of northern Australia, Fire Ecol., 11(1), 10–31, doi:10.4996/fireecology.1101010, 2015.

Oliveras, I., Meirelles, S. T., Hirakuri, V. L., Freitas, C. R., Miranda, H. S. and Pivello, V. R.: Effects of fire regimes on herbaceous biomass and nutrient dynamics in the Brazilian savanna, Int. J. Wildl. Fire, 22(3), 368–380, doi:10.1071/WF10136, 2013.

Pellegrini, A. F. A., Ahlström, A., Hobbie, S. E., Reich, P. B., Nieradzik, L. P., Staver, A. C., Scharenbroch, B. C., Jumpponen, A. and Anderegg, W. R. L.: Fire frequency drives decadal changes in soil carbon and nitrogen and ecosystem productivity,

https://doi.org/10.5194/bg-2020-86
Preprint. Discussion started: 20 April 2020

Nature, doi:10.1038/nature24668, 2018.

Penman, T. D., Christie, F. J., Andersen, A. N., Bradstock, R. A., Cary, G. J., Henderson, M. K., Price, O., Tran, C., Wardle, G. M., Williams, R. J. and York, A.: Prescribed burning: how can it work to conserve the things we value?, Int. J. Wildl. Fire, 20(6), 721, doi:10.1071/WF09131, 2011.

Pivello, V. R.: The use of fire on the cerrado and amazonian rainforrests, Fire Ecol., 7(1), 24–39, doi:10.4996/fireecology.0701024, 2011.

Price, O. F., Russell-smith, J. and Watt, F.: The influence of prescribed fire on the extent of wildfire in savanna landscapes of western Arnhem Land, Australia, Int. J. Wildl. Fire, 21, 297–305, doi:10.1071/WF10079, 2012.

Ramos-Neto, M. B. and Pivello, V. R.: Lightning Fires in a Brazilian Savanna National Park: Rethinking Management Strategies, Environ. Manage., 26(6), 675–684, doi:10.1007/s002670010124, 2000.

Reid, J. S., Koppmann, R., Eck, T. F., Eleuterio, D. P., Division, M., Juelich, F. and County, B.: A review of biomass burning emissions part II : intensive physical properties of biomass burning particles, Atmos. Chem. Phys., 5(3), 799–825, doi:10.5194/acp-5-799-2005, 2005.

Ribeiro, J. F. and Walter, B. M. T.: As principais Fitofisionomias do Bioma Cerrado, in Cerrado: ecologia e flora, pp. 152–212., 1998.

Rissi, M. N., Baeza, J., Gorgone-barbosa, E., Zupo, T. and Fidelis, A.: Does season affect fire behaviour in the Cerrado ?, Int. J. Wildl. Fire, 26, 427–433, doi:10.1071/WF14210, 2017.

Russell-smith, J., Monagle, C., Jacobsohn, M. and Sánchez-rose, I.: Can savanna burning projects deliver measurable greenhouse emissions reductions and sustainable livelihood opportunities in fire-prone settings ?, Clim. Change, 47–61, doi:10.1007/s10584-013-0910-5, 2017.

Schmidt, I. B., Moura, L. C., Ferreira, M. C., Eloy, L., Sampaio, A. B., Dias, P. A. and Berlinck, C. N.: Fire management in the Brazilian savanna: First steps and the way forward, J. Appl. Ecol., (October 2017), 1–8, doi:10.1111/1365-2664.13118, 2018.

Scott, K., Setterfield, S. A., Douglas, M. M., Parr, C. L., Schatz, J. O. N. and Andersen, A. N.: Does long-term fire exclusion in an Australian tropical savanna result in a biome shift ? A test using the reintroduction of fire, , 693–711, doi:10.1111/j.1442-9993.2012.02379.x, 2012.

Sexton, J. O., Song, X. P., Feng, M., Noojipady, P., Anand, A., Huang, C., Kim, D. H., Collins, K. M., Channan, S., DiMiceli, C. and Townshend, J. R. G.: Global, 30-m resolution continuous fields of tree cover: Landsat-based rescaling of MODIS Vegetation Continuous Fields with lidar-based estimates of error., Int. J. Digit. Earth, doi:10.1080/17538947.2013.786146., 2013.

Shindell, D. and Faluvegi, G.: Climate response to regional radiative forcing during the twentieth century, Nat. Geosci., 2(4), 294–300, doi:10.1038/ngeo473, 2009.

Silva, M. (Ministério do M. A., Luiz Barroso Barros, M. (Instituto B. do M. A. e R. N. R., Bueno, H. (Prevfogo N. and Bernardino, dos santos, M. (Estação E. S. G. do T.: Florestais Na Estação Ecológica De Serra Geral Do Tocantins (Região Do Jalapão), Palmas., 2005.

Smith, T. E. L., Evers, S., Yule, C. M. and Gan, J. Y.: In Situ Tropical Peatland Fire Emission Factors and Their Variability, as Determined by Field Measurements in Peninsula Malaysia, Global Biogeochem. Cycles, 32(1), 18–31, doi:10.1002/2017GB005709, 2018.

Staver, A. C., Archibald, S. and Levin, S. A.: The Global Extent and Determinants of Savanna and Forest as Alternative Biome States, Science (80-.)., 334(6053), 230–232, doi:10.1126/science.1210465, 2011.

Sudo, K. and Akimoto, H.: Global source attribution of tropospheric ozone: Long-range transport from various source regions,

J. Geophys. Res. Atmos., 112(12), doi:10.1029/2006JD007992, 2007.

Surawski, N. C., Sullivan, A. L., Meyer, C. P., Roxburgh, S. H. and Polglase, P. J.: Greenhouse gas emissions from laboratory-scale fires in wildland fuels depend on fire spread mode and phase of combustion, Atmos. Chem. Phys., 15(9), 5259–5273, doi:10.5194/acp-15-5259-2015, 2015.

Surawski, N. C., Sullivan, A. L., Roxburgh, S. H., Meyer, C. P. M. and Polglase, P. J.: Incorrect interpretation of carbon mass balance biases global vegetation fire emission estimates, Nat. Commun., 7(May), 1–5, doi:10.1038/ncomms11536, 2016.

Susott, R. A., Olbu, G., Baker, S. P., Ward, D. E., Kauffman, J. B. and Shea, R. W.: Carbon, hydrogen, nitrogen, and thermogravimetric analysis of tropical ecosystem biomass, in Biomass Burning and Global Change: Remote sensing, modeling and inventory Development and Biomass Burning in Africa, edited by J. S. Levine, pp. 350–360, MIT Press, Cambridge, Mass., 1996.

Townshend, J. R. G., Carroll, M., Dimiceli, C., Sohlberg, R., Hansen, M. and DeFries, R.: Percent Tree Cover, Collection 6, Veg. Contin. Fields MOD44B, 2011.

Urbanski, S.: Forest Ecology and Management Wildland fire emissions , carbon , and climate : Emission factors, For. Ecol. Manage., 317, 51–60, doi:10.1016/j.foreco.2013.05.045, 2014.

Urbanski, S. P.: Combustion efficiency and emission factors for wildfire-season fires in mixed conifer forests of the northern Rocky Mountains, US, Atmos. Chem. Phys., 13(14), 7241–7262, doi:10.5194/acp-13-7241-2013, 2013.

Veenendaal, E. M., Torello-raventos, M., Miranda, H. S., Sato, N. M., Oliveras, I., Langevelde, F. Van, Asner, G. P., Lloyd, J. and Lloyd, J.: On the relationship between fire regime and vegetation structure in the tropics, new phytoogist, doi:10.1111/nph.14940, 2018.

Ward, D. E., Setzer, A. W., Kaufman, Y. J. and Rasmussen, R. A.: Characteristics of smoke emissions from biomass fires of the Amazon region - BASE-A experiment, in Global Biomass Burning - Atmospheric, Climatic and Biospheric Implications, edited by J. S. Levine, pp. 394–401, The MIT press., 1991.

Ward, D. E., Susott, R. A., Kauffman, J. B., Babbitt, R. E., Cummings, D. L., Dias, B., Holben, B. N., Kaufman, Y. J., Rasmussen, R. A. and Setzer, A. W.: Smoke and fire characteristics for cerrado and deforestation burns in Brazil : BASE-B Experiment, J. Geophys. Res. Atmos., (December 2013), doi:10.1029/92JD01218, 1992.

van der Werf, G. R., Randerson, J. T., Giglio, L., van Leeuwen, T. T., Chen, Y., Rogers, B. M., Mu, M., van Marle, M. J. E., Morton, D. C., Collatz, G. J., Yokelson, R. J. and Kasibhatla, P. S.: Global fire emissions estimates during 1997–2016, Earth Syst. Sci. Data, 9(2), 697–720, doi:10.5194/essd-9-697-2017, 2017.

Winter, F., Wartha, C. and Hofbauer, H.: NO and N2O formation during the combustion of wood, straw, malt waste and peat, Bioresour. Technol., 70(1), 39–49, doi:10.1016/S0960-8524(99)00019-X, 1999a.

Winter, F., Wartha, C. and Hofbauer, H.: The Relative Importance of Radicals on the N2O and NO Formation and Destruction Paths in a Quartz CFBC, J. Energy Resour. Technol., 121(2), 131–136, doi:10.1115/1.2795068, 1999b.

Wooster, M. J., Freeborn, P. H., Archibald, S., Oppenheimer, C., Roberts, G. J., Smith, T. E. L., Govender, N., Burton, M. and Palumbo, I.: Field determination of biomass burning emission ratios and factors via open-path FTIR spectroscopy and fire radiative power assessment: Headfire, backfire and residual smouldering combustion in African savannahs, Atmos. Chem. Phys., 11(22), 11591–11615, doi:10.5194/acp-11-11591-2011, 2011.

Yates, C. P., Russell-smith, J., Murphy, B. P., Desailly, M., Evans, J., Legge, S., Lewis, F., Lynch, D. and Edwards, A. C.: Fuel accumulation, consumption and fire patchiness in the lower rainfall savanna region, in Carbon Accounting and Savanna Fire Management, edited by B. P. Murphy, A. C. Edwards, M. Meyer, and J. Russell-smith, pp. 115–127, CSIRO Publishing., 2015.

Yokelson, R. J., Goode, J. G., Ward, D. E., Susott, R. A., Babbitt, R. E., Wade, D. D., Bertschi, I., Griffith, D. W. T. and Hao,

https://doi.org/10.5194/bg-2020-86
Preprint. Discussion started: 20 April 2020

W. M.: Emissions of formaldehyde, acetic acid, methanol, and other trace gases from biomass fires in North Carolina measured by airborne Fourier transform infrared spectroscopy, J. Geophys. Res. Atmos., 104(D23), 30109–30125, doi:10.1029/1999JD900817, 1999.

Yokelson, R. J., Burling, I. R., Urbanski, S. P., Atlas, E., Adachi, K., Buseck, P. R., Wiedinmyer, C., Akagi, S. K., Toohey, D. W. and Wold, C. E.: Trace gas and particle emissions from open biomass burning in Mexico, Atmos. Chem. Phys., 11(14), 6787–6808, doi:10.5194/acp-11-6787-2011, 2011.

Yokelson, R. J., Burling, I. R., Gilman, J. B., Warneke, C., Stockwell, C. E., Gouw, J. De and Akagi, S. K.: Coupling field and laboratory measurements to estimate the emission factors of identified and unidentified trace gases for prescribed fires, Atmos. Chem. Phys., 13, 89–116, doi:10.5194/acp-13-89-2013, 2013.

https://doi.org/10.5194/bg-2020-86
Preprint. Discussion started: 20 April 2020

Table 1: Number of samples and ancillary information about the field campaigns.

Vegetation class	Fractional tree cover	Fire-frequency 2013-2018	% of EESGT	EDS samples	LDS samples
Open grassland (campo limpo/campo sujo)	0-5 %	3.4 years	17.6 %	162	122
Open cerrado (Cerrado ralo)	5-20 %	3.8 years	35.6 %	310	113
Typical cerrado (Cerrado típico / Cerrado strictu sensu)	20-50 %	4.0 years	25.1 %	20	35
Gallery forest (Mata de Galeria/Mata Ciliar)	Continuous canopy	8.6 years	3.0 %	0	23
Riparian zones (Campo limpo Úmido/Veredas)	Sparse palm trees	3.7 years	9.6 %	0	12

https://doi.org/10.5194/bg-2020-86
Preprint. Discussion started: 20 April 2020

Table 2: Description of analysis equipment used

Analysis equipment	Technique	Gas species	Measurement precision	Calibration gas Concentration	Calibration gas accuracy
Los Gatos micro-portable CO_2/CH_4 analyzer	Off-axis integrated-cavity output spectroscopy	CO_2 CH_4	2 ppmv 3 ppbv	4968 ppmv 15.71 ppmv	2% 5%
Aeris Pico mid-IR Laser-based CO/N_2O analyzer	Cavity ring-down spectroscopy	CO N_2O	1 ppbv 1 ppbv	103.0 ppmv 1.15 ppmv	2% 2%

https://doi.org/10.5194/bg-2020-86
Preprint. Discussion started: 20 April 2020

Table 3: Weighted mean EF for various vegetation types for EDS and LDS fires. The standard error of the mean is given in parentheses.

Vegetation	Season	samples	EF CO_2	EF CO	EF CH_4	EF N_2O
Open grassland (campo limpo/campo sujo) 0-5% tree cover	EDS: LDS: $\Delta_{LDS-EDS}$(%)	162 122	1661 (3) 1675 (4) +1%*	49 (1.8) 43 (2.0) -13%	0.74 (0.03) 0.70 (0.04) -6%	0.081 (0.01) 0.032 (0.04) -61%*
Open cerrado (cerrado ralo) 5-20% tree cover	EDS: LDS: $\Delta_{LDS-EDS}$(%)	310 113	1672 (2) 1685 (7) +1%	45 (1.2) 38 (3.7) -16%	0.69 (0.02) 0.64 (0.06) -7%	0.122 (0.01) 0.149 (0.02) +22%
Typical cerrado (cerrado típico) 20-50% tree cover	EDS: LDS: $\Delta_{LDS-EDS}$(%)	20 35	1657 (6) 1676 (10) +1%	52 (3.4) 43 (5.3) -18%	0.90 (0.04) 0.71 (0.10) -21%	0.099 (0.01) 0.153 (0.01) +54% *
Gallery forrest (mata de galeria/mata ciliar)	EDS: LDS:	0 23	- 1668 (27)	- 80 (13.2)	- 2.06 (0.43)	- 0.514 (0.09)
Humid grassland (campo limpo úmido/veredas)	EDS: LDS:	0 12	- 1822 (24)	- 185 (37.9)	- 5.93 (0.39)	- 0.399 (0.07)
Cerrado $\overline{EF}$ (weighted by % BA 2013-2018)	EDS: LDS: $\Delta_{LDS-EDS}$(%)		1664 1679 +1%	48 41 -15%	0.78 0.68 -13%	0.105 0.123 +17%

***** *difference is statistically significant (p < 0.05)*

https://doi.org/10.5194/bg-2020-86
Preprint. Discussion started: 20 April 2020

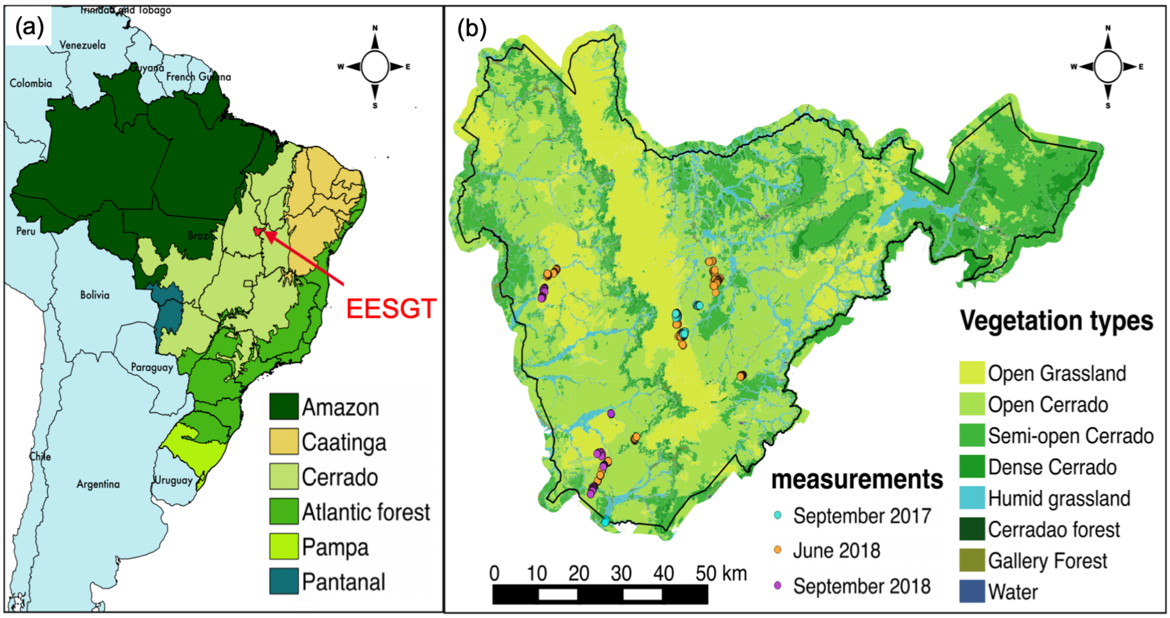

Figure 1: a) Location of the Estação ecológica Serra Geral in the Cerrado biome in the Brazilian state of Tocantins. b) Vegetation types in the estação ecológica Serra Geral from the University of Brasilia (Carlos and Filho, 2017) with the locations of the measurements.

https://doi.org/10.5194/bg-2020-86
Preprint. Discussion started: 20 April 2020

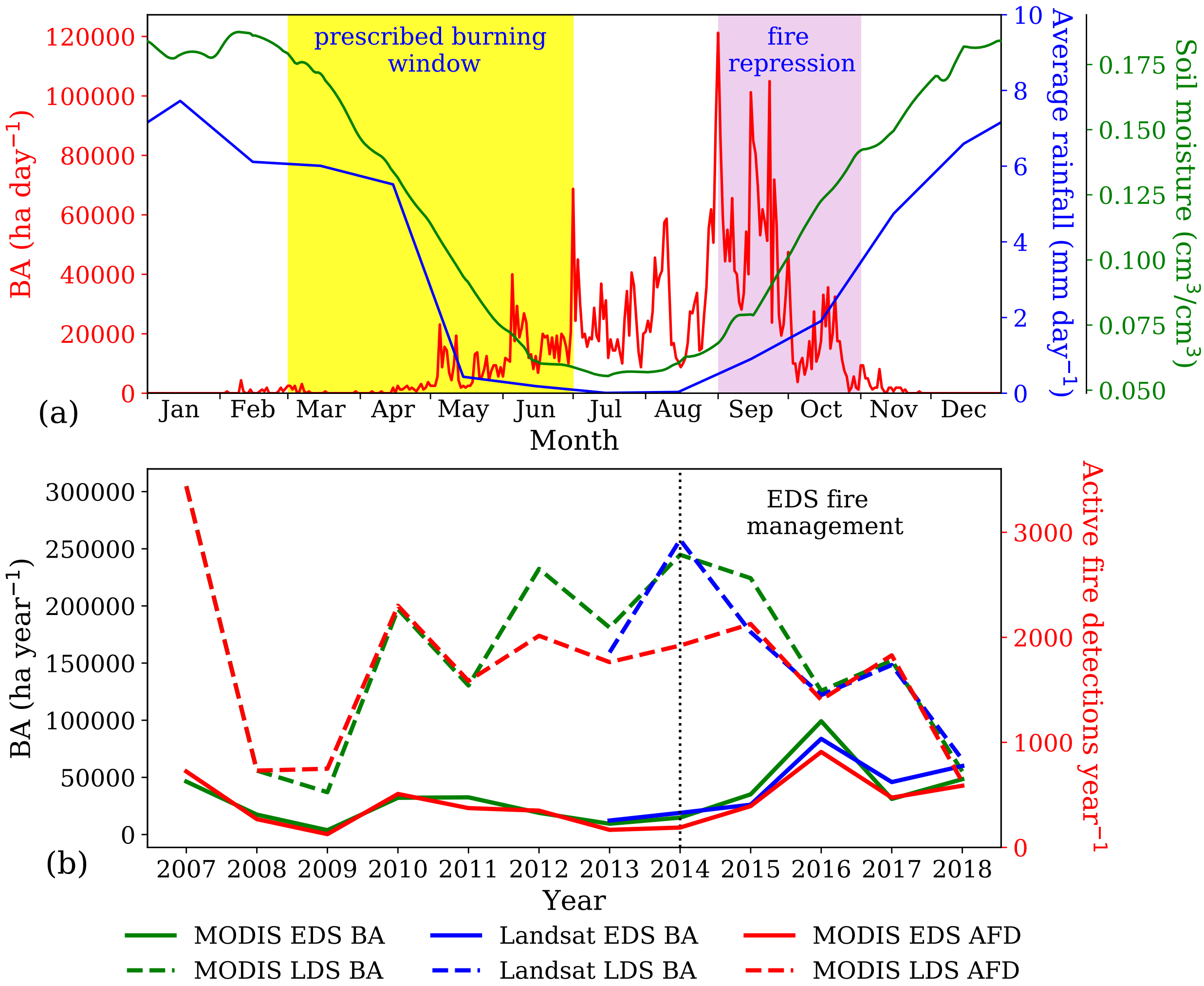

Figure 2. Seasonality and inter-annual variability of satellite-derived fire metrics, rainfall, and soil moisture. (a) Daily burned area (BA; MCD64A1 C6) as well as monthly rainfall and soil moisture, averaged over the 2013-2018 period. The prescribed burning season and repression season are hatched. (b) Early dry season (EDS) and late dry season (LDS). annual burned area and active fire detections (AFD, MOD14A1v6/MYD14A1v6 (Giglio and Justice, 2015)) over the 2007-2018 period.

https://doi.org/10.5194/bg-2020-86
Preprint. Discussion started: 20 April 2020

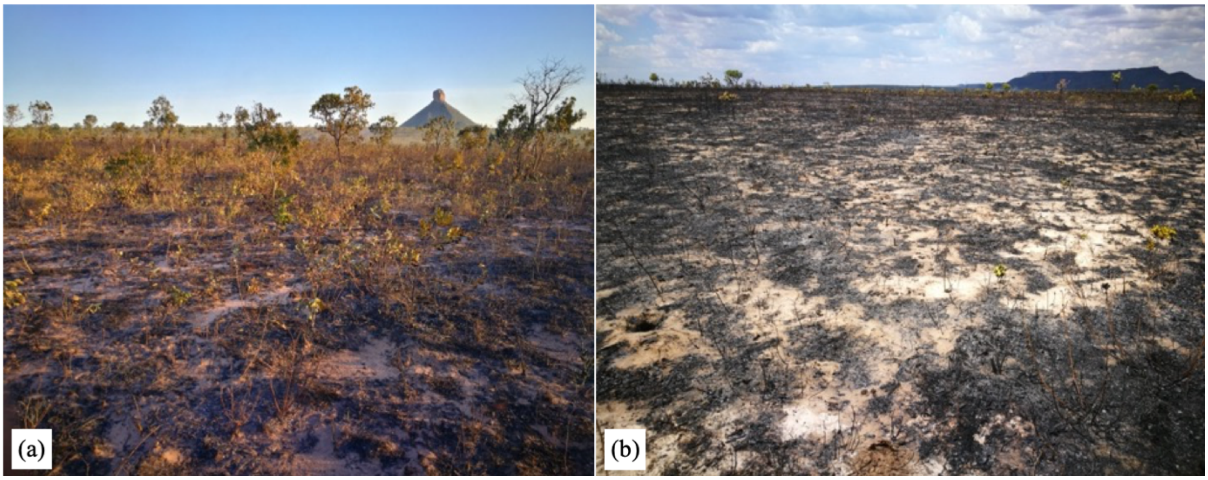

Figure 3: Typical post-fire images showing the much smaller impact of EDS fires, in this case in June (left), compared to LDS fires in September (right).

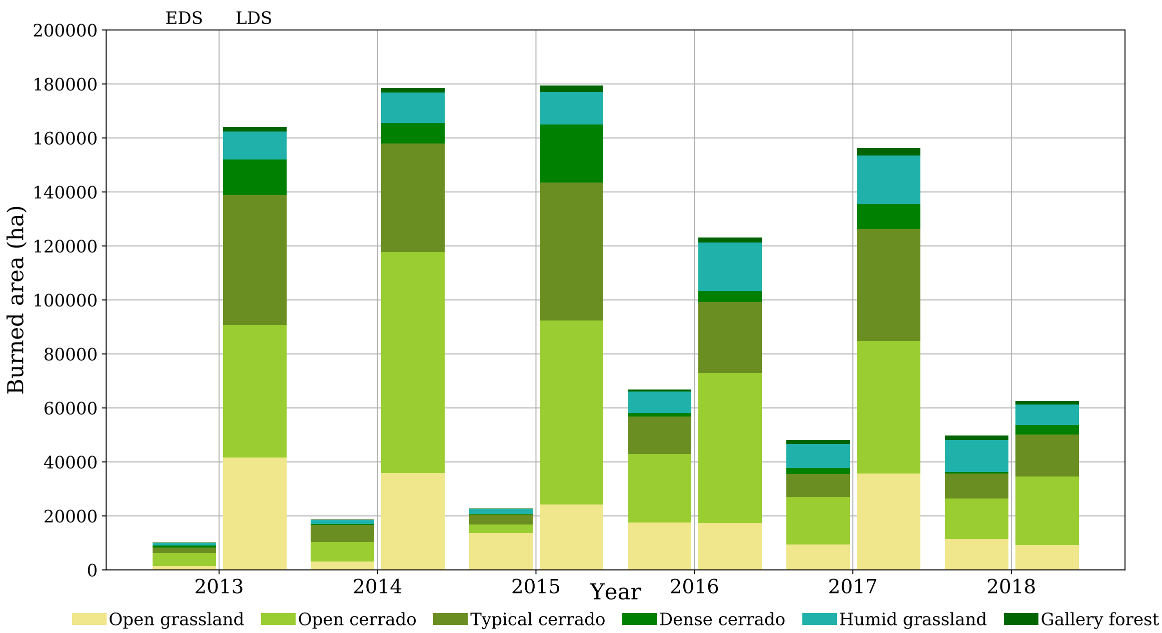

Figure 4: Partitioning of the burned area over the EDS (before July 1st) (left columns) and LDS (after July 1st) (right columns) for the various vegetation types.

https://doi.org/10.5194/bg-2020-86
Preprint. Discussion started: 20 April 2020

Biogeosciences Discussions
Open Access
EGU

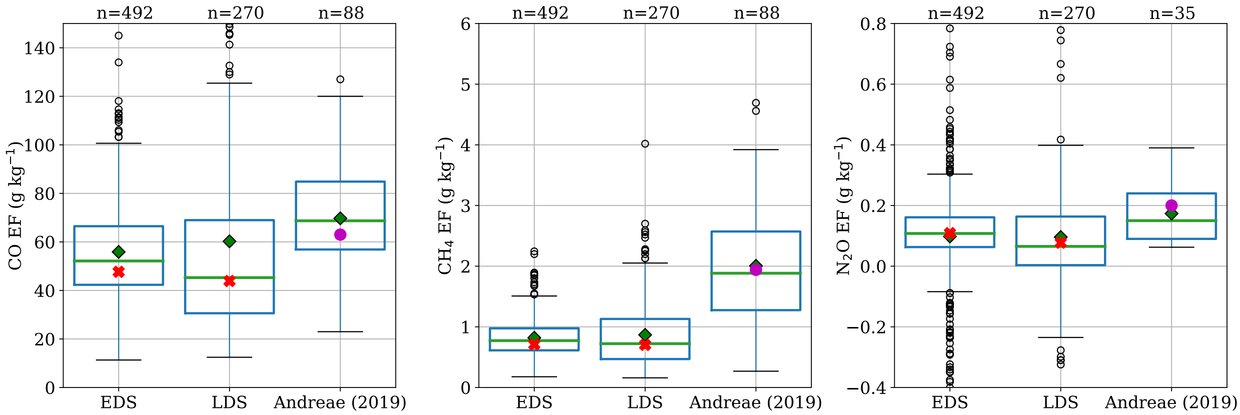

Figure 5: EFs in the EDS and LDS as well as the EFs from savanna measurements used in the Andreae (2019) EF compilation. The green diamond represents the arithmetic mean and the red cross represents the EMR-weighted mean value. The purple dot represents the value that is used in GFED for savanna fires.

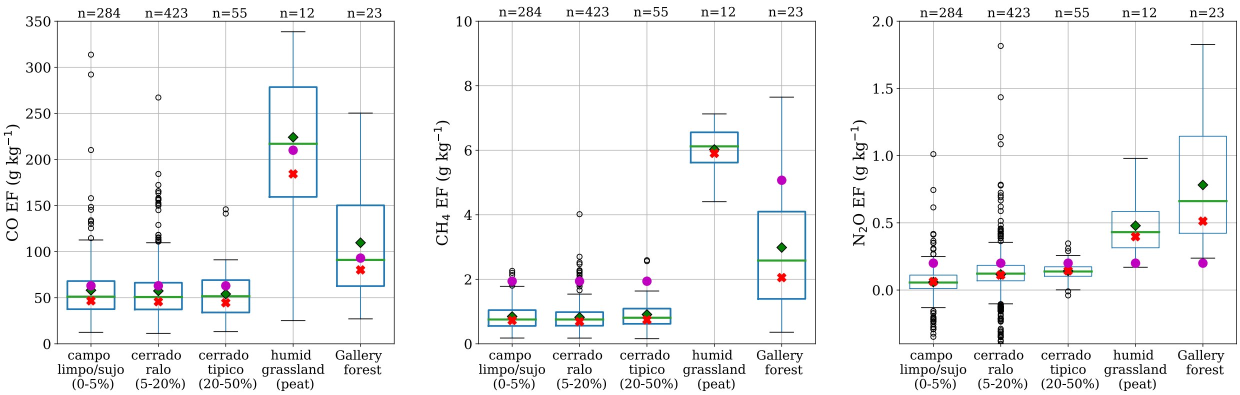

Figure 6: EFs of CO, CH_4, and N_2O for the various vegetation types. The green diamond represents the arithmetic mean and the red cross represents the EMR-weighted mean. The purple dot represents the values that are used in GFED for 'savanna', 'peat' and 'tropical deforestation' fires respectively.

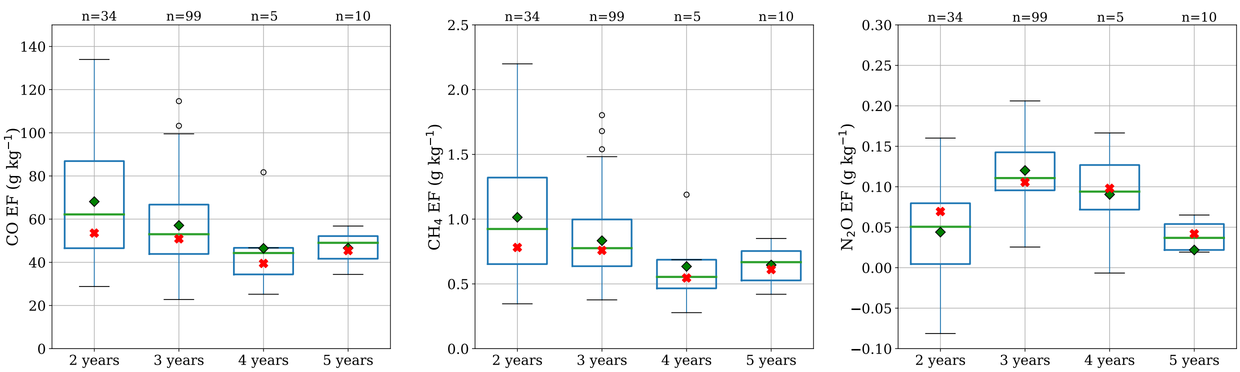

Figure 7: EFs for CO, CH_4, and N_2O for open grassland samples for different periods since last fire. The green diamond represents the arithmetic mean and the red cross represents the EMR-weighted mean.

https://doi.org/10.5194/bg-2020-86
Preprint. Discussion started: 20 April 2020

Biogeosciences
Discussions
Open Access

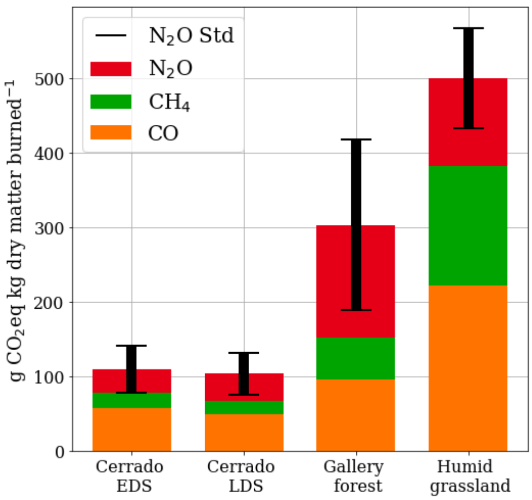

Figure 8: CO_2 equivalents using GWP with a 100-year horizon and including indirect atmospheric effects for various fire types. The bar represents the ± one standard deviation range of the N_2O measurements.

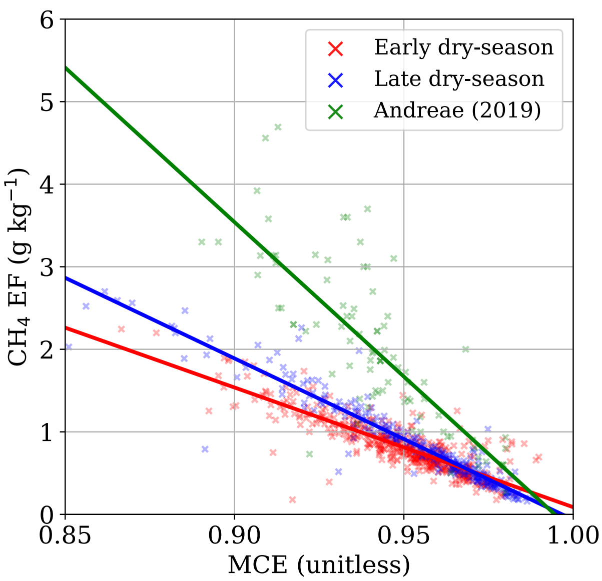

Figure 9: Relation between the CH_4 EF and the MCE for all EDS and LDS samples from cerrado vegetation fires (i.e. excluding humid grasslands and gallery forest samples). Existing savanna measurements are shown using the study-average values in the Andreae (2019) database.

https://doi.org/10.5194/bg-2020-86
Preprint. Discussion started: 20 April 2020

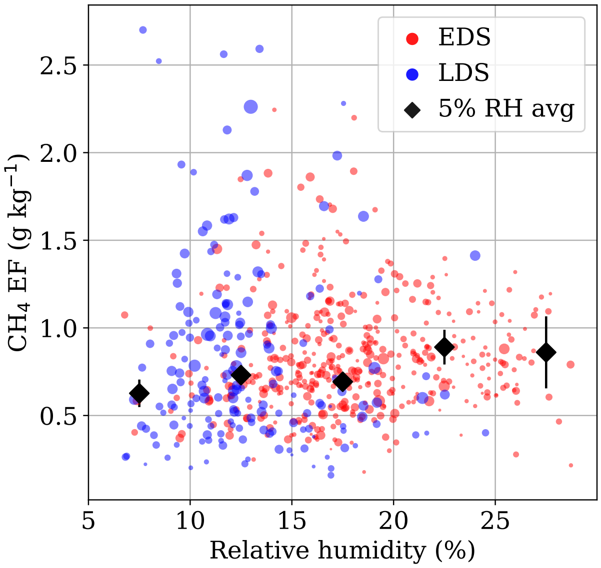

Figure 10: CH_4 EFs as a function of relative humidity based on measurements on the UAV at the time of sampling. The size of the dots represents the ΔCH_4 EMR (ppm) in the sample and therefore depicts relative contribtion to the weighted mean. The black diamonds show the weighted average CH_4 EF for each 5% relative humidity bin. The black line represents the standard error of the class' mean.

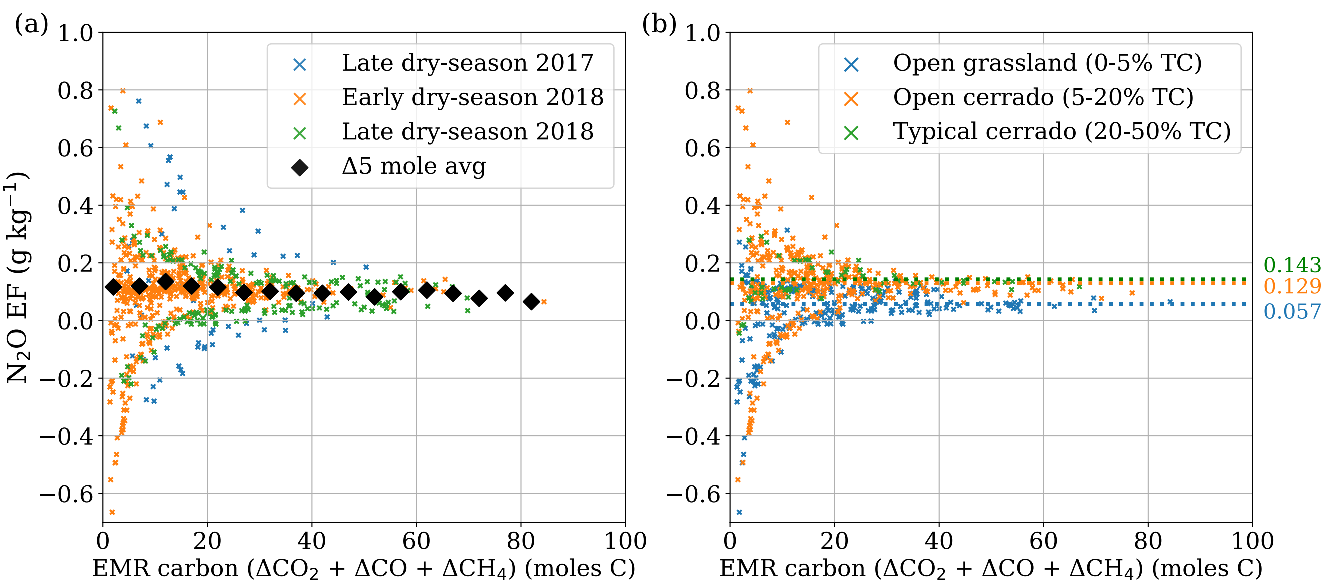

Figure 11: N_2O EFs plotted against the cumulative EMR of the carbonaceous trace gases in the sample based on a) all cerrado measurements in the three campaigns. The black diamonds represent the averages of each 5 mole C bin. b) Combined EDS and LDS measurements in open grasslands, open cerrado and typical cerrado vegetation. The dotted lines and numbers on the right represent the weighted average N_2O EFs over all campaigns.