EPISODIC NITROUS OXIDE SOIL EMISSIONS IN BRAZILIAN SAVANNA (CERRADO) FIRE-SCARS

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ABSTRACT

The seasonally burned cerrados of Brazil are the largest savanna-type ecosystem of South America and their contribution to the global atmospheric nitrous oxide (N$_2$O) budget is unknown. Four types of fire-scarred cerrado along a vegetation gradient from grassland to forest were investigated during the wet season of 1992/93. The effect of fire and subsequent water additions on episodic emissions of N$_2$O, and the associated profile dynamic of soil-gas-phase N$_2$O concentrations were studied for several months. Additionally, the effect on episodic emissions of N$_2$O of nitrate and glucose additions to a cerrado soil after fire and the associated profile dynamic of soil-gas-phase N$_2$O mixing ratios, was determined. Finally, N$_2$O episodic emissions in cerrado converted to corn, soybean and pasture fields were investigated during one growing/wet season.

Results showed N$_2$O consumption/emission for the four fire-scarred savanna ecosystems, for nitrogen and carbon fertilization and for agriculture/pasture ranging from -0.3 to +0.7, 1.8 to 9.1, and 0.5 to 3.7 g N$_2$O-N · ha$^{-1}$ · d$^{-1}$, respectively. During the wet season the cerrado biome does not appear to be a major source of N$_2$O to the troposphere, even following fire events. However, the results of this study suggest that conversion of the cerrado to high input agriculture, with liming and fertilization, can increase N$_2$O emissions more than ten fold.
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Introduction

Nitrous oxide (N\textsubscript{2}O), the third most important anthropogenic greenhouse trace-gas after carbon dioxide (CO\textsubscript{2}) and methane (CH\textsubscript{4}), has been increasing in the global troposphere at a rate of close to 0.3 \% per year (Khalil and Rasmussen, 1983; Khalil and Rasmussen, 1992; Prinn, Cunnold et al., 1990; Weiss, 1981). Unlike CO\textsubscript{2} and CH\textsubscript{4}, for which major global sources are reasonably well known, important atmospheric sources of N\textsubscript{2}O are not yet quantified or even identified (Kim and Craig, 1993; Robertson, 1993). Of the presently known sources, soils are estimated to be the largest (e.g. Robertson, 1993 and references therein), with tropical soils expected to account for most of the emissions (e.g. Griffiths et al., 1993; Keller et al., 1983; Matson and Vitousek, 1987; Robertson and Tiedje, 1986; Seiler and Conrad, 1987).
The Brazilian savannas (sensu Huntley and Walker, 1982), known collectively as the cerrado biome, occupy 1.88 million km² (Pereira, 1982), second in area only to the Amazonian rainforest in South America. These frequently burned tropical expanses have become a potentially important source for greenhouse trace-gas species. On a worldwide basis, 1.8, 2.4 and 2.6 times more biomass is burned annually in savannas than burned in agriculture, forests, and as firewood, respectively (Levine, 1991). That volume of biomass could produce 3 to 4 times greater emissions of trace gases from direct fire than burning for deforestation in tropical rainforests (Hao et al., 1990).

On burned sites (fire-scars) post-fire soil processes, including trace-gas exchange with the atmosphere, can be considerably different from unburned sites (e.g. Andreae et al., 1988; Anderson and Domsch, 1989; Crutzen, 1985; Delmas, 1982; Fishman et al., 1986). The potential importance of post-fire change in emissions of nitrous oxide and other trace-gases was first identified by (Anderson et al., 1988) and (Levine et al., 1988), but prior to this work had not yet been studied for the cerrados in South America.
Because of good soil aeration, favorable temperatures, and comparatively more NH$_4$-N than NO$_3$-N availability, nitrification may be the most important pathway for N$_2$O production in the cerrado soils, while denitrification would be rare due to high acidity and high permeability to atmospheric O$_2$ (Pereira, 1982; Robertson and Tiedje, 1987). Once vegetation is burned, depending on fire intensity, most of the nitrogen in various forms is released from the biomass (Tamm, 1991). Meteorological conditions during and after fire determine how much of the ammonia, nitrate and aerosols released by the fire will return to the system in dry and wet precipitation, and how much will be subject to long-range atmospheric transport (Andreae, 1992). Another important effect of fire on the ecosystem is the release of other basic nutrients in the ashes, which temporarily diminishes aluminum saturation and raises soil pH (Coutinho, 1990), consequently changing conditions for the nitrogen biogeochemistry in the soil. Additionally, following fire consumption of plant aerial parts, the short-term termination of plant nutrient uptake contributes to larger transient pools of NH$_4^+$ and NO$_3^-$ in the soil. Nitrate, however, is quickly leached from the cerrado soils (Suhet and Ritchey, 1981 cited in Pereira, 1982).

Studies of another tropical savanna in South America during the dry season suggested that production of N$_2$O would be larger in the wet
Agricultural soils converted from cerrado vegetation are especially important for their significance as one of the most extensive land-use changes occurring on the planet. And the potential for increasing episodic emissions to become significant due to heavy nitrogen fertilization as these natural ecosystems are converted to agriculture or pasture has been widely recognized (e.g. Vitousek and Matson, 1993; Duxbury et al., 1993).

In this paper, we report on a study carried out on a range of savanna ecosystems after prescribed fire disturbance. The study was designed to measure the N$_2$O emissions in fire-scared cerrado ecosystems during the wet season. Additionally, nitrogen and carbon fertilization experiments were conducted in fire scars, and N$_2$O emissions were measured in three well established agricultural fields of corn, soybean and pasture. The study was carried out at a site with ongoing long term ecological fire disturbance studies (Instituto Brasileiro do Meio Ambiente / Projeto Fogo).

**Methods**

**Study Site**

The Roncador reservation, a 1300 ha ecological station of the Instituto Brasileiro de Geografia e Estatistica (IBGE), lies 35 km to the
south of Brasilia, the Brazilian capital, within the federal district (15° 56' 41" S; 47° 53' 07" W, from 1048 to 1150 m asl approx. elevation), in the core zone of the central Brazilian pre-Cambrian shield. The terrain of the reserve is mostly developed on Tertiary detritic-lateritic sediments (CODEPLAN, 1984). The local climate, as for most of central Brazil, is seasonal, an Aw in the Köpen classification. The dry season extends roughly from May to September, and the variation in air temperature is moderate between seasons. Annual climatic means are: temperature, approximately 21°C, 1667 mm precipitation and 1200 mm potential evapotranspiration (Pereira et al., 1989).

The N$_2$O flux measurements in the fire-scars (FScars) were conducted for four types of savanna vegetation (Table II.1) which encompassed the full range of physiognomic forms (Figure II.1) for the cerrado sensu lato (Coutinho, 1990). In spite of the great heterogeneity of vegetation, local climate and soils occurring over this South American biome (e.g., Coutinho, 1990; Dias, 1992; Santos, 1988), the cerrado physiognomic forms represented in the four sites chosen for this study can be found on approximately 78% of the Brazilian savannas (Dias, 1992). All sites except the campo limpo (savanna grassland) were located on the most extensive high plateaus. The dominant soil on these plateaus falls within the oxisol order in the USDA classification (USDA, 1975), and is
classified as a *latossolo vermelho-escuro álisco*, clayey-distrophic, in the Brazilian classification (Pereira et al., 1989). This soil, representative of soils covering 43% of the cerrado biome (Adámoli et al., 1986), is very permeable, has low water retaining capacity and is very deep. The natural fertility on its superficial layer is very low, with high acidity and high exchangeable aluminum levels (Table II.2) (Pereira, 1982). The savanna grassland site was located on a lower slope formed from a broad alluvial Cenozoic plain. The soil was hydromorphic and not classified but possibly a *gley humic* in the Brazilian classification.

The savanna fertilization experiment (FertEx) was carried out on a plot of cerrado *sensu stricto* (wooded savanna) which had not been burned since 1989.

The agriculture/pasture experiments (APEX) were conducted on nearby commercial plantations within a radius of 36 km from the Roncador reservation. All three sites were located on plateau oxisols equivalent to those for the upland Roncador reservation, and had been under cultivation for at least 10 years.
Experimental Design

The experimental plots used in this study are part of a longer term experiment carried out to study the effect of prescribed fire on diverse aspects of the cerrado vegetation and direct-fire emissions to the atmosphere (Projeto Fogo). The design has five 500 x 200 m plots for each system: tree\shrub savanna (Cs), wooded savanna (Ct) and savanna woodland (Cd), (see Table II.3), and two larger irregular plots for savanna grassland (Cl). Within one five-plot block the plots were organized as follows: one plot unburned for the last 18 years (control), one plot burned in 1991 (year) and three plots burned in 1992 (one in the early dry season, June, another in the mid dry season, August, and the last in the late dry season, September). The two plots for Cl were: one plot burned in 1989 and one plot burned in 1992 (late dry season, September). Only the plots burned in the late dry season of 1992 were chosen for the FScars episodic N$_2$O emission experiments in this study.

Because N$_2$O production and consumption in soil are discontinuous over time (e.g. Brumme and Beese, 1992; Davidson et al., 1991; Grundmann and Rolston, 1987; Johnsson et al., 1991; Mosier et al., 1991; Sexstone et al., 1985; Terry et al., 1981) sampling in this study was designed to document episodic processes. For the episodic measurements in FScars, in FertEx and in APEX, each of the experimental sites had one
1.6 x 3.2 m plot subdivided into two 2.56 m² sub-plots (repetitions). Each sub-plot was 1.6m-sided square with two basic components or installations: one PVC ring or collar inserted approximately in the center of the square, and one array of stainless steel soil-gas-phase probes (except for year and control plots at the Cs site and agriculture/pasture sites) for sampling at various depths, installed to one side of the collar and extending under it.

The simulated rain events were water/solution additions applied using a garden watering can. The water or solutions were sprinkled evenly onto the sub-plots over a period of 15 minutes so that they would percolate into the soil without forming standing water. For each simulated rain event, measurements were done at time zero, which immediately preceded the additions, and then at 30 minutes, 2, 4, and 8 hours, one day after the additions, and daily thereafter until completion of the experiment. Each series of measurements associated with one simulated rain event is called here simply Event #x, x being just a sequence number. Single flux measurements did not have time-steps. The distribution of episodic measurements for each treatment as well as additions for FScars, FertEx and APEx during the wet season can be found in Tables II.3, II.4 and II.5 respectively.

In FertEx the treatment plots were contiguous and were contained within a radius of 10 m. All the nitrogen and carbon sources
were dissolved immediately before irrigation in local well-water. Event #1 (Table II.4) occurred 2 days before the prescribed fire, with the original unburned vegetation in place. For this event only water was added and only for one plot (two repetitions). Due to frequent rain, the prescribed fire could occur only after the experimental area had been protected from rain for three weeks. The fire was set at noon time and burned quickly and well (white ash). The collars set up for Event #1 (control) were removed before the fire, and reinstalled after the fire in the same positions. For Event #2 (Table II.4), there were three fertilizer treatments and a control with water alone. The fertilizers were sodium nitrate (NaNO$_3$) at a level of 50 kg N · ha$^{-1}$ as the first fertilizer treatment, glucose (dextrose, $\alpha$-D(+)_C$_6$H$_{12}$O$_6$) at a level of 250 kg C · ha$^{-1}$ as the second treatment, and nitrate at 50 kg N · ha$^{-1}$ plus glucose at 250 kg C · ha$^{-1}$ as the third treatment. The 5:1 C:N ratio used to obtain denitrifying potential was similar to that used in soil core incubation studies (Parsons et al., 1993; Schuster and Conrad, 1992).

For APEx, all fields had received lime (CaCO$_3$), corn had received nitrogen fertilizer prior to the experiment, and soybean seeds had been inoculated with *Rhizobium japonicum* nitrogen-fixing bacteria. At each agricultural site one collar was positioned between plants within a row, and the repetition was placed between rows. At the pasture site, one
collar went on the soil between grass clumps, and the other directly on a 
grass clump. The history of previous cropping and fertilization was not 
available, however, these sites represented well established agribusiness 
enterprises. The scope for each agriculture experiment was limited to two 
episodic measurements, the first done approximately one month after 
planting, and the second near harvest, approximately 100 days after 
planting (Table II.5). The scope for the pasture experiment was limited to 
one episodic measurement done at the beginning of the wet season, and 
then one single flux measurement done 100 days later (Table II.5).

Field Sampling

The chamber enclosure technique used to quantify trace-gas 
exchange between soil and atmosphere has been widely used and is 
discussed at length by (Hutchinson and Livingston, 1993). The technique 
used was identical to the one used for the study discussed in Chapter 1. 
In this study, the two-part static vented-chambers consisted of a 25 cm 
internal diameter, 10 cm tall, polyvinylchloride (PVC) ring or collar and a 
molded acrylonitrile-butadiene-styrene (ABS) plastic top, 10 cm tall, with 
a gas sampling port, a pressure equilibration port, and a lip that fit over 
the PVC ring (Matson et al., 1990). The chamber top was well aerated 
before the beginning of each N₂O flux measurement. The lip of the top 
was greased lightly with silicon grease (Apiezon) and the collar capped
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tightly with it. Gas samples, withdrawn through an injection port at 1, 7, 14, 21 and 28 minutes after closure, were collected using 20 ml nylon syringes (S.E.S.I., VWR Scientific), each fitted with two butyl rubber o-rings (greased with Apiezon), and polypropylene stopcocks (Baxter Scientific). Each flux measurement consisted of a five syringe sample set (see Appendix A for detail in method), after which the chamber closure was opened. Air temperature was taken during the sampling. Nitrous oxide flux was calculated by regressing the linear change over time of the N₂O mixing ratio in the chamber enclosure (Keller et al., 1986).

One week prior to the experiment the collar was inserted approximately 2 cm into the top soil. The reduced root mat coverage in the cerrado, compared with the Amazonian ecosystems, was similar to the La Selva sites, in that enhanced gas emissions with early insertion of rings into the soil was not a problem (see Part I and Matson et al., 1990). The sampling of soil-gas was carried out, similarly to the procedure used in La Selva, using horizontal probes made of stainless steel tubing (3.17 mm od) formed into an L shape, installed adjacent to the PVC collar, at depths of 2, 5, 10, 20, and 40 cm (similar to those in Figure I.1). The drawing portion of the probe tubing, approximately 10 cm long, had 20 small holes drilled through the wall, distributed along its length. The upper part of the L (2 cm) was bonded (epoxy setting glue) to a capillary
stainless steel tubing (1.59 mm OD) leading upward outside the soil. On top, a cut-off hypodermic needle (1.59 mm OD) with a luer slip lock was hooked to the stainless steel tubing, tip to tip, using a short piece of polystyrene tubing. During the intervals between sampling, a plastic cap was used on the slip lock end to seal the probe from the atmosphere and from dirt.

Laboratory Analysis

Nitrous oxide was determined for one 2 ml sub-sample for each 20 ml field sample, using a Mini2 Shimadzu gas chromatograph fitted with stainless steel columns (3.2 mm OD by 2 m), packed with 50-80 mesh HaySep (backflush column) and 50-80 mesh Porapaq Q (main column), and a $^{63}$Ni electron capture detector. Operating conditions were: column temperature, 70° C; electron capture detector temperature, 300° C; P5 mixture (95% Ar with 5% CH$_4$) carrier gas with a flow rate of 30 ml · min$^{-1}$. The gases N$_2$O and CO$_2$ were separated, but only N$_2$O mixing ratios were quantified. Oxygen was removed from the carrier gas using an oxygen trap (Altech Oxy-Trap™), and hydrocarbons, CFC's, etc. were removed with a mol-sieve purifier filter. Water vapor was removed from all samples with a pre-column of moisture absorbent (CaSO$_4$ - Dryrite™). The standards used in the analysis were nitrous oxide in dinitrogen gas mixtures, at 338, 513 and 971 ppbv (Scott Specialty Gases), with the
lowest (338 ppbv) calibrated against NOAA (Nitrous Oxide and Halocarbons Division, Climate Monitoring and Diagnostics Laboratory, Boulder, Colorado) secondary standards. The precision of this instrument was 1.9 % (standard deviation / mean). The minimum flux of $\text{N}_2\text{O}$ that could be detected with this system over a 28-min period at 25°C was 0.3 g $\text{N}_2\text{O}-\text{N} \cdot \text{ha}^{-1} \cdot \text{d}^{-1}$.

**Results and Discussion**

**Savanna Fire-Scar Experiments (FScars)**

Figures II.2 and II.3 show time series data on experimental results for soil-gas-phase $\text{N}_2\text{O}$ mixing ratios profiles and $\text{N}_2\text{O}$ fluxes.

**Savanna Grassland (Cl)**. At the Cl site, $\text{N}_2\text{O}$ averaged fluxes were either negative or remained close to background levels throughout the measured period after fire (Figure II.2.A). The single measurements made 15/Nov/92, 55 days after fire (d.a.f.), and 18/Feb/93, 150 d.a.f., showed that the $\text{N}_2\text{O}$ mixing ratios to depths of 20 cm were either lower or indistinguishable from atmospheric mixing ratios (ambient, 310 ppb). The apparent difference between the two dates in the gas profile can be directly tied to soil moisture. The water table was very close to the surface, oscillating between 20 to 30 cm. In November, well into the wet season, the...
soil column above the water table was so saturated that the sampling of soil-gas could not be done without unintentionally collecting soil water into the syringes. The mixing ratios reported here are those of the syringe headspace. There seemed to be a sink for N\textsubscript{2}O at this date, given the somewhat strong downward gradient in the soil. Waterlogging induces anaerobiosis, which in turn promotes N\textsubscript{2}O reduction to N\textsubscript{2} (for a review of denitrification in subsurface environments see Rice and Rogers, 1993). In February of 1993 there had been a veranico (short dry spell in the wet season) during the time of the second measurement. On the second date, the soil sampling showed no N\textsubscript{2}O mixing ratio gradients in the profile, indicating neither production nor consumption with depth. Most likely this was due to the dryer conditions, but also due to vigorous growth of grass on the surface, indicating low nitrogen substrate availability for denitrification. The water addition two days after the second measurement of the flux and the gas profile made fluxes slightly negative. However, the magnitude of this change was not meaningful because it was below detection limit (BDL) for this study.

If one assumes that these few measurements are representative of fire-scar emission behavior, it is possible that during the wet season burned C\textsubscript{1} savannas may be a net sink for tropospheric N\textsubscript{2}O. But with the highest measured sink-flux only 1 g N\textsubscript{2}O-N \cdot ha\textsuperscript{-1} \cdot d\textsuperscript{-1} it is unlikely that
this kind of savanna, which covers only 5.5% of the cerrado (Table II.1),
is of major importance in the overall cerrado N$_2$O budget.

**Tree/shrub savanna (Cs).** Forty three days after fire (29/Oct/92) the N$_2$O soil mixing ratio profile for Cs (Figure II.2.B) showed a consistent episodic pulse production after 20 mm of simulated rainfall. However, the N$_2$O pulse is best expressed at 5 cm depth and does not translate into higher fluxes at the surface; with the exception of the flux which occurred two hours after simulated rain, all other fluxes for Event #1 fell below detection level. At time 0, immediately before the simulated rainfall, a weak gradient of N$_2$O mixing ratios existed with depth, which could indicate increased background production with increasing depth. During pulse progression, a time lag occurred with greater mixing ratios with increasing depth (10, 20 and 40 cm), which indicated that the pulse for those depths resulted mostly from downward diffusion of N$_2$O. That can be a corroboration on the inference that N$_2$O is being produced primarily in the layer from 2 to 5 cm deep. Eight hours after simulated rainfall, the episodic pulse was over, and the mixing ratio gradient was reduced to virtually zero, a condition which remained unchanged until the end of the episodic measurement at 24h. An estimated integrated production of 0.2 g N$_2$O-N · ha$^{-1}$ (·24h$^{-1}$) fell BDL (Figure II.3.A; Table II.6).
For Event #2, 150 days after fire, there was a small background emission of 1 g N$_2$O-N \cdot ha$^{-1}$ \cdot d$^{-1}$ before the simulated rainfall (Figure II.3.A). After 20 mm water addition most other flux measurements fell BDL. The soil N$_2$O mixing ratio showed a much less intense pulse throughout the profile than observed during the pulse in Event #1, but indicated some brief disturbance associated with the water addition (Figure II.2.B). The Event #2 disturbance could be ascribed to physical displacement of soil atmosphere by percolating water, and to some momentary gas build up due to waterlogging of diffusional pathways from production microsites (or production in deeper layers) to the atmosphere. The estimated integrated production of 0.1 g N$_2$O-N \cdot ha$^{-1}$ \cdot d$^{-1}$ in a one day episodic flux fell BDL (Table II.6).

The two other treatments with single measurements in the tree/shrub savanna, which is the control plot burned 18 years before the experiments, and the year plot burned in 1991 (one year before the 92 prescribed fires), showed similar flux behavior (Figure II.3.A).

In conclusion, during the wet season the Cs savanna showed very weak or undetectable N$_2$O fluxes to the atmosphere, be it quasi-climax, 18
years after fire (a.f.), an imperceptible fire-scar (1 year + a.f.), or a still fresh fire-scar (less than two to more than five months a.f.). If this kind of vegetation, which occupies nearly 12% of the cerrado biome (Table II.1), were to become of any potential importance as a net source of N₂O, it very likely would not be from emissions occurring during the main part of the wet season.

**Wooded Savanna (Ct)**. The N₂O soil gas profiles for Ct (Figure II.2.C) for 9/Nov and in 8/Dec/92, showed no episodic pulse associated with simulated rainfall for additions. For Event #1, the water addition lead to a progressive decrease in mixing ratios for up to 8 h from simulated rainfall. For Event #2, the water addition lead to a progressive increase in mixing ratios up to 4 h after the simulated rainfall. Throughout the profile time series for both events, a slight upward mixing ratio gradient was noticed, which should translate into some flux to the atmosphere on the surface. However, from the six flux measurements over the course of each event, only three in Event #1 and only two in Event #2 were slightly above detection limit.

The single measurement for 28/Feb/93, 166 d.a.f. (Figure II.2.C), shows a close similarity with the undisturbed condition in Event #2, 84 d.a.f.. The integrated gas production for both events showed that over one day the amount of gas
emitted/consumed fell BDL or slightly above, with 0.6 g N\textsubscript{2}O-N \cdot ha\textsuperscript{-1} in Event #2 (Figure II.3.B; Table II.6).

During the wet season, a fire-scared Ct savanna (less than two, three and more than five months a.f.) showed very weak or undetectable N\textsubscript{2}O episodic or background fluxes to the atmosphere. Thus, emissions during the main part of the wet season for this vegetation, which occupies 53 % of cerrado biome (Table II.1), probably will not become important as a net source of N\textsubscript{2}O.

**Savanna Woodland (Cd)**. From the two events in the Cd savanna, only the second, 70 d.a.f., produced an episodic pulse, most intense at 2 h after simulated rainfall (Figure II.2.D). In the first event, 1/Nov/92, 40 d.a.f., water addition seemed to have slightly depressed soil N\textsubscript{2}O mixing ratios. Nevertheless, for both events and for almost all time-steps, there was a weak upward gradient in soil-gas N\textsubscript{2}O mixing ratios. Noteworthy here was the sizable difference in fluxes between repetitions, indicating a strong spatial heterogeneity. The integrated fluxes for both events showed either a non-detectable or a very low N\textsubscript{2}O emission (Figure II.3.C; Table II.6).

The savanna woodland showed that despite weak upward soil N\textsubscript{2}O gradients, and a detectable pulse in soil N\textsubscript{2}O mixing ratios, fluxes at
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the soil surface were less than 0.3 g N₂O-N · ha⁻¹ · d⁻¹. With 8.3 % cover for the cerrado biome (Table II.1), during the wet season this kind of savanna is not likely to be of key importance for overall ecosystem N₂O emissions.

Cerrado FScars Emissions in Comparison with Emissions in other Similar Ecosystems

Hao et al. (1988) measuring N₂O emissions during the dry season from soils in Gran Sabana ecosystems, Venezuela, found a mean flux from undisturbed plots to be 0.5 g N₂O-N · ha⁻¹ · d⁻¹. The fluxes were not significantly affected by burning the grass layer, but increased 5 fold upon water addition. Matson et al. (1991) studying sagebrush steppe ecosystems in Wyoming, USA, found annual mean N₂O fluxes varying from 0.03 to 1 g N₂O-N · ha⁻¹ · d⁻¹ with an area-average of 0.6 g N₂O-N · ha⁻¹ · d⁻¹. Mosier et al. (1991) studying two native grasslands in North America found fluxes of 1.8 and 3 g N₂O-N · ha⁻¹ · d⁻¹.

The range of values found for N₂O emissions in the present study were similar. The fluxes for the Gran Sabana were the closest to the ones measured for the Brazilian cerrados (FScars), despite measurements in different seasons, suggesting that the nitrogen
biogeochemistry for all tropical savannas in South America may be similar. The increase in flux after simulated rainfall in the dry season (Hao et al., 1988), and the lack of comparatively increased fluxes during the wet season, suggests that in the tropical savannas the main N$_2$O episodic emission should occur in the transition from the dry to the wet season, similarly to what was reported for a tropical deciduous forest in Mexico (Garcia-Mendez et al., 1991).

The Savanna Fertilization Experiment (FertEx)

In FertEx there are three important aspects that complement the information from FScars. The first is that the measurements made immediately before the fire event for Event #1 were made at the same site. The second aspect is water was added immediately following the fire. All the simulated rainfalls for FScars happened more than one month after fire, which missed the loss/gain of nitrogen substrates due to the fire itself, the immediate impact of ash input to the soil, and the temporary cessation of vegetative absorption of substrate from the soil. The third aspect of FerEx that complements FScars is that substrate/fertilizers were added in the former so that the differentiated N$_2$O emission response could provide clues to the biogeochemical limitations in the soil.
**Control Treatment.** For the control treatment, measurements taken both before and after the fire event showed clear responses to water addition (Figure II.4.A). The effect of fire on the water stimulated pulses was clear throughout the profile, but was most intense at depths of 5 and 10 cm. The briefness of these pulses indicated an intermediate transient pool of N₂O during nitrate reduction to N₂. The absence of lags in the pulses throughout the profile corroborates this interpretation, because N₂O was reduced before it had time to diffuse up and down.

In the pre-fire Event #1, the small episodic pulse was reflected on the soil surface with a small flux peak, which did not translate into positive emissions into the atmosphere (Figure II.5.A). For both events there were weak upward mixing ratio gradients. Integrated fluxes showed that Event #1, with plants present, produced no N₂O in 24 h, while Event #2, with the ashes from the fire, produced 1.8 g N₂O-N \( \cdot \) ha\(^{-1}\) in 96 h (0.45 g N₂O-N \( \cdot \) ha\(^{-1}\) \( \cdot \) d\(^{-1}\)) (Figure II.5.A). This latter flux is only slightly above detection limit (Table II.7).

This control treatment in FertEx showed that immediately after fire, the behavior of N₂O episodic gas emission in a wooded savanna during the wet season is not substantially different than that of other similar systems, at one, two and five+ months after fire. However, these
experiments do not represent the soil biogeochemical state at the end of the dry season when substrate for denitrification has accumulated from decomposition and mineralization/nitrification. Most fires occur at the end of the dry season (August/September). So the prescribed fire in January for FertEx did not represent the soil conditions at the end of the dry season because a considerable volume of rain had percolated through the soil by that time, leaching substrates and stimulating biogeochemical processes to consume them. This prescribed fire was interesting insofar as it produced a sudden release of ashes on the previously protected and dry soil, and because it destroyed plants, ceasing plant nutrient absorption temporarily.

**Nitrate-N Treatment.** The Nitrate-N treatment clearly showed that nitrate is the most limiting substrate for N₂O production in this soil (Figure II.4.B). First, the pulses for Event #2 were broader, indicating that the nitrous oxide formed into a transient pool was not quickly consumed, and had time to diffuse out into the atmosphere. The fluxes measured on the soil surface showed a clearly distinguishable pulse associated with the pulse inside the soil profile. Second, the overall production of 4.3 g N₂O-N·ha⁻¹ in 96 h (1.1 g N₂O-N·ha⁻¹·d⁻¹) was more than twice that of the control and glucose treatments (Figure II.5.B; Table II.7). However, this emission response was less than half of that
for the equivalent treatment in a Costa Rican volcanic sandy soil (Vegas Nitrate-N, Part I), and one order of magnitude smaller than that for a volcanic clayey soil (Flaminia Nitrate-N, Part I).

**Glucose-C Treatment.** The profile results for Event #2 in the Glucose-C treatment showed a lack of extra response to water + glucose, if compared with water alone (Figure II.4.C). For comparison, the data plotted for Event #1 is the same as that for the control treatment. As in the control treatment, there were weak upward mixing ratio gradients, and the integrated production showed the same production as with water alone, that is 1.8 g N₂O-N·ha⁻¹ in 96 h (0.45 g N₂O-N·ha⁻¹·d⁻¹) (Figure II.5.C; Table II.7). The fact that glucose did not produce enhanced emissions here, as opposed to the increments in emissions observed in Costa Rica (Part I), is an indication that there are other limitations to denitrification in the Brazilian savanna, most likely a very low level of nitrate availability in the soil.

**Nitrate-N + Glucose-C Treatment.** A surprising result of this treatment was enhancements in N₂O mixing ratios for Event #2 throughout the period of observation, most intense at depths 10 and 20 cm (Figure II.4.D). Also striking were the differences between the two repetitions
and the temporal extent of the enhancement. The gas production in the soil began with the addition of water + substrates, but it did not come back to the background level after the few hours as was common for most peaks in the other treatments. A synergistic effect between nitrate and glucose was evident. Glucose alone did not produce an effect, nitrate alone doubled emissions, and nitrate plus glucose quadrupled emissions; thus, compared with nitrate alone glucose helped the system to use up nitrate with doubled efficiency.

Total emission of 9.1 g N$_2$O-N · ha$^{-1}$ in 96 h (2.3 g N$_2$O-N · ha$^{-1}$ · d$^{-1}$) was about twenty times less than that of the equivalent treatment in the Costa Rican sandy Vegas soil, and one order of magnitude less than that of the equivalent treatment in clayey Flaminia soil (Part I) (Figure II.5.D; Table II.7).

**Agriculture/Pasture Experiments (APEx)**

**Corn** (*Zea mays*). In the Corn field, the emissions of Event #1 were the most striking and consistent of all APEx episodic measurements (Figure II.6.A). The highest emissions were found between rows, precisely where nitrogen fertilizer ((NH$_4$)$_2$SO$_4$) was spread prior to the crop planting. Emissions within rows, where plant roots developed and supposedly absorbed most nutrients, were minimal. The total averaged
emission of \( \frac{3.7 \, \text{g} \, \text{N}_2\text{O-N} \cdot \text{ha}^1}{24 \, \text{h}} \) in 24 h is equivalent to that of the Nitrate-N treatment of FertEx (Tables II.7 & II.8).

More than three months later, near the harvest, the emissions for Event #2 were minimal, with little difference between inter- or intra-row measurements. The total averaged emission of \( \frac{0.6 \, \text{g} \, \text{N}_2\text{O-N} \cdot \text{ha}^1}{24 \, \text{h}} \) was six times smaller than the emissions in Event #1 and slightly above detection limit, indicating the possibility that the system was depleted of nitrogen substrate due to plant absorption, leaching and/or nitrification/denitrification gaseous losses (Table II.8).

In a review of \( \text{N}_2\text{O} \) emissions from fertilized soils, Eichner (1990) listed four studies in temperate corn fields for which results ranged from 0.0 to 25.9 g \( \text{N}_2\text{O-N} \cdot \text{ha}^1 \cdot \text{d}^1 \), and averaged of 12 g \( \text{N}_2\text{O-N} \cdot \text{ha}^1 \cdot \text{d}^1 \). Mosier and Hutchinson (1981) studying \( \text{N}_2\text{O} \) emissions for the whole cycle of an irrigated corn plantation in northern Colorado, USA, found that on the average the system emitted 35.8 g \( \text{N}_2\text{O-N} \cdot \text{ha}^1 \cdot \text{d}^1 \). They also found that approximately 30 % of the \( \text{N}_2\text{O} \) was emitted during the first two weeks following fertilization, while \( \text{NH}_3 \) was being rapidly nitrified, and 59 % was emitted during the week following the first irrigation of the field, when restricted oxygen diffusion favored
denitrification. These facts suggest that the two episodic measurements in the present study might have missed the main emission periods soon after fertilization and soon after the first rainfalls.

In another similar study of N$_2$O plus N$_2$ loss from denitrification on corn and barley fields in northern Colorado, Mosier et al. (1986) showed, that in the corn field, about 70% of the total N gas emitted was N$_2$O. Based on this result, it was concluded that denitrification might play a smaller role in agricultural gaseous nitrogen loss than was traditionally believed. The present study agrees with that conclusion; the lack of episodic pulses following simulated rainfall suggests that denitrification is not a major pathway for N$_2$O production in this soil.

**Soybean (Glycine max)**. Unlike the corn field, emissions from the soybean field increased with time (Figure II.6.B), which can be an indication that *Rhizobium* fixed nitrogen was being liberated into the soil. With 1.29 g N$_2$O-N • ha$^{-1}$ in 24 h, 2.6 times more N$_2$O was emitted, on average, for Event #2 than for Event #1 (Table II.8).

Here, similar to the corn field, water addition depressed emissions strongly. So in dry weather it is likely that emissions would be
many times larger than the totals registered in the two events here, as the flux measurements made before water additions indicate. Because atmospheric N\textsubscript{2} fixed by \textit{Rhizobium} first becomes NH\textsubscript{4}, nitrification must proceed before nitrogen substrate is available for denitrification. The fact that water addition depressed N\textsubscript{2}O emission, instead of enhancing it as in systems where denitrification is strong, suggests that nitrification is the main pathway for N\textsubscript{2}O production in this agroecosystem.

Annual average N\textsubscript{2}O emissions measured by \textit{Bremner} et al. (1980), from soybeans fields on six different temperate soils, ranged from 0.9 to 5.4 g N\textsubscript{2}O-N \cdot ha\textsuperscript{-1} \cdot d\textsuperscript{-1}. More than ten years ago, \textit{Pereira} (1982) estimated that the approximate nitrogen input to the Brazilian cerrados via fixation in soybean crop fields would be 0.15 \cdot 10\textsuperscript{9} Kg N \cdot yr\textsuperscript{-1}, for a soybean production of about 3 \cdot 10\textsuperscript{9} Kg \cdot yr\textsuperscript{-1}. \textit{Eichner} (1990) estimated total world wide N\textsubscript{2}O emissions from fields of cultivated legumes to be 23 to 315 Gg N\textsubscript{2}O-N in 1986. Soybean is one of the most important cash crops in the cerrado biome. Because soybean does not require nitrogen fertilization, it is generally planted in infertile soils, and after several growing seasons the harvest debris is turned under until the incorporated plant biomass renders the soils more fertile for other more demanding crops, like corn or wheat.
Pasture (Paspalum grass). Water addition in the pasture site strongly depressed emissions for a short while. The total production over Event #1 of 0.5 g N₂O-N·ha⁻¹ in 24 h (Figure II.6.C) was equivalent to Event #1 in the soybean field and Event #2 in the corn field (Table II.8). This production was also marginally larger than the minimum flux detection limit for the system used to measure it, and did not differ substantially from most events in the experiments of FScars upland plateaus. The differences in emissions from a grass clump to the sample between grass clumps indicated an effect of plant absorption on the overall availability of substrate for nitrification. Production in dry weather appeared to be greater than that with rain events. The single measurement made two months after the episodic measurement also did not show any extraordinary production. Pastures might be a relevant source of N₂O only in those areas fertilized directly by animal urine and feces.

The magnitude of N₂O emissions found for this pasture was 5 to almost 300 times smaller than that found for pastures of varying ages after deforestation of Costa Rican rainforests (Keller et al., 1993), or 10 to 50 times smaller than a fertilized pasture in the Amazon (Luizão et al., 1989). Compared with emissions in temperate grasslands on sandy loam soils, for this study N₂O emissions still were 5 times smaller than the
unfertilized pasture and 12 times smaller than the fertilized pasture
(Mosier et al., 1991).

Pastures are one of the most characteristic uses of the savannas of central Brazil because they somewhat resemble the original system. Extensive areas of savanna grassland and tree/shrub savanna are historically used for low intensity cattle ranching. Some areas are totally disturbed, with substitution of original grasses by exotic species and by liming and fertilization, in addition to cultural practices like the use of fire and decompaction (plowing) to periodically renew the grass. The pasture studied here was one under intensive management.

Importance of the Conversion of Cerrado to High Input Agriculture

Large scale human interference in the nitrogen cycle is recognized as one of the most likely causes of the increasing $N_2O$ atmospheric mixing ratio (IPCC, 1990). The land-use conversion rate for the last twenty years in the Brazilian cerrado has been alarming (Dias, 1992). By 1982, the area permanently cleared in savannas each year world-wide was half the area cleared in forests (Lanly, 1982).
Despite edaphic and hydric limitations of the cerrado natural soils, factors like their excellent topography and texture for mechanized agriculture; together with liming, fertilization and irrigation techniques; low labor and land acquisition costs; extensive network of roads and proximity to major export corridors and consumer centers have rendered these ecosystems very attractive for high input cash-crop agribusiness enterprises, which are rapidly transforming this region into one of the largest grain belts in the world (Dias, 1992; Pereira, 1982).

Besides the attractions for agricultural frontier expansion, there are no provisions in the new Brazilian Constitution for the protection of savanna ecosystems (Dias, 1992) as there are for the Amazonian and Atlantic rainforests, and for other less extensive biomes under attack by encroaching development. Unless external factors change the dynamics of the present explosive frontier expansion, like fluctuations in cash-crop market prices, in time a total conversion of the Brazilian cerrados into high input agroecosystems will be almost unavoidable. Given this scenario, it is of paramount importance that the impact of this continental conversion of savanna ecosystems be better studied for its role as a potential additional source for radiatively active trace-gases.
Conclusions

The series of experiments with fire scared savanna soils, fertilization and fire effects and agriculture/pasture emissions of N$_2$O reported in this paper indicate that water additions do not stimulate intense pulses of N$_2$O emissions in this soil system.

The data in the N$_2$O mixing ratios profiles showed strong temporal coherence among the several layers, although the biogeochemical interpretation could not explain disagreement between the patterns observed in the soil and some of the associated patterns of emissions on the soil surface.

In the fertilization experiments, N$_2$O emissions were found to respond differently depending on which kind of fertilizer was used. The fact that nitrogen (but not carbon) produced a response, and that carbon could only enhance N$_2$O response when both substrates were applied together suggests that these soils were critically limited in nitrogen substrate. Small pulses of production could develop quite superficially in the soil, especially between 5 to 10 cm, and can develop to a maximum
strength within the range of 30 min. to 2 hours. The episodic part of the flux occurring in brief transient oscillations in the background flux after a rain event could not differentiate the emission regimen. Those episodic faint pulses associated with liquid amendment varied slightly in intensity and duration among treatments. For the Fire-Scars and for the Agriculture/Pasture the depression in fluxes promoted by water addition suggested a lack of denitrification for these soils. The higher emission rate on dryer soil suggested that nitrification is the main biogeochemical \( N_2O \) production pathway.

During the wet season the cerrado biome does not appear to be a major source of \( N_2O \) to the troposphere, even following fire events. However, the results of this study suggest that conversion of the cerrado to high input agriculture, with liming and fertilization, can increase \( N_2O \) emissions more than ten fold.

The cerrado biome as such, and during the wet season does not seem to be a major source of \( N_2O \) to the troposphere, not even after fire events. However, the results of this study have suggested that its conversion to high input agriculture, with liming and fertilization, can increase \( N_2O \) emissions more than ten times.
Acknowledgment

This study was supported by a grant from the National Aeronautics and Space Administration (NASA #(?)). During the course of this study A.D. Nobre was a Doctoral Fellow of the NASA Global Change Research Program at the University of NH, Durham. We thank the Instituto Brasileiro de Meio Ambiente (IBAMA), and Universidade de Brasilia for their assistance in the field and lab, and the Instituto Brasileiro de Geografia e Estatistica (IBGE) for the infrastructure at the Roncador reservation. We thank also the staff of the Roncador Reservation for their support. The mention of product trade names does not imply endorsement by NASA.

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Savanna Fire and N₂O Response


Nobre, Crill & Harriss  

Savanna Fire and N$_2$O Response


Nobre, Crill & Harriss

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Savanna Fire and $\text{N}_2\text{O}$ Response


Nobre, Crill & Harriss


Savanna Fire and N₂O Response


Table II.1. Vegetation types and general properties for the savannas in central Brazil

<table>
<thead>
<tr>
<th>Abbreviation - Type (portuguese name)</th>
<th>Area in 1000 km² (% of total for the biome)</th>
<th>Density trees/ha</th>
<th>Tree canopy cover %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cl - Savanna grassland (campo limpo)</td>
<td>112 (5.5)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Cs - Tree and/or shrub savanna (campo sujo)</td>
<td>236 (11.6)</td>
<td>500</td>
<td>&lt; 2</td>
</tr>
<tr>
<td>Ct - Wooded savanna (cerrado sensu stricto)</td>
<td>1080 (53.0)</td>
<td>1000</td>
<td>2 - 15</td>
</tr>
<tr>
<td>Cd - Savanna woodland (cerrado denso ou Cerradão)</td>
<td>169 (8.1)</td>
<td>3000</td>
<td>15 - 40</td>
</tr>
</tbody>
</table>

* from Sarmiento (1983) and Azevedo & Adamoli (1988)
Table II.2. Main superficial soil properties for the savannas in central Brazil

<table>
<thead>
<tr>
<th>Soil Parameter</th>
<th>Vegetation Type (portuguese name)</th>
<th>Ct - Savanna grassland (campo limpo)</th>
<th>Cs - Tree/shrub savanna (campo sujo)</th>
<th>Ct - Wooded savanna (cerrado sensu stricto)</th>
<th>Cd - Savanna woodland (cerrado denso)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay (%)</td>
<td></td>
<td>33</td>
<td>36</td>
<td>34</td>
<td>32</td>
</tr>
<tr>
<td>Silt (%)</td>
<td></td>
<td>20</td>
<td>16</td>
<td>15</td>
<td>16</td>
</tr>
<tr>
<td>Sand (%)</td>
<td></td>
<td>46</td>
<td>18</td>
<td>51</td>
<td>53</td>
</tr>
<tr>
<td>pH (H₂O)</td>
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<td>4.9</td>
<td>4.9</td>
<td>5.0</td>
<td>5.1</td>
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<td>Organic C (%)</td>
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<td>2.2</td>
<td>2.3</td>
<td>2.4</td>
<td>2.3</td>
</tr>
<tr>
<td>CEC (meq%)</td>
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<td>1.1</td>
<td>1.2</td>
<td>1.4</td>
<td>1.8</td>
</tr>
<tr>
<td>Al⁺ (meq%)</td>
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<td>0.7</td>
<td>0.6</td>
<td>0.7</td>
<td>0.6</td>
</tr>
<tr>
<td>Al⁺ Sat. (%)</td>
<td></td>
<td>66</td>
<td>58</td>
<td>54</td>
<td>44</td>
</tr>
<tr>
<td>Ca (meq%)</td>
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<td>0.3</td>
<td>0.5</td>
<td>0.7</td>
</tr>
<tr>
<td>Mg (meq%)</td>
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<td>0.1</td>
<td>0.2</td>
<td>0.4</td>
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<tr>
<td>K (meq%)</td>
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<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
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<tr>
<td>P (ppm)</td>
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<td>0.5</td>
<td>0.5</td>
<td>0.9</td>
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<td>Zn (ppm)</td>
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<td>0.6</td>
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<td>0.7</td>
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<td>Cu (ppm)</td>
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<td>0.8</td>
<td>0.9</td>
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<td>Mn (ppm)</td>
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<td>5.4</td>
<td>10.3</td>
<td>15.9</td>
<td>22.9</td>
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</tbody>
</table>

* data from Lopes (1975, cited in Santos, 1988); average of 520 samples
### Table II.3. Vegetation types and treatments for Savanna Fire-Scars Experiment (FScars)

<table>
<thead>
<tr>
<th>Abbreviation - Type (portuguese name)</th>
<th>Site's Last Fire in</th>
<th>Episodic Event#1</th>
<th>Episodic Event#2</th>
<th>Single Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>CI - Savanna grassland (campo limpo)</td>
<td>Sept/21/92</td>
<td>none</td>
<td>20mm water</td>
<td>Nov/15/92</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>[55 d.a.f]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Feb/18/93</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>[150 d.a.f]</td>
</tr>
<tr>
<td>Ct - Wooded savanna (cerrado sensu stricto)</td>
<td>Sept/16/92</td>
<td>20mm water</td>
<td>20mm water</td>
<td>Feb/28/93</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Nov/9/92</td>
<td>Dec/8/92</td>
<td>[166 d.a.f]</td>
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<td></td>
<td></td>
<td>[55 d.a.f]</td>
<td>[84 d.a.f]</td>
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<td>Cd - Savanna woodland (cerrado denso ou Cerradão)</td>
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<td>20mm water</td>
<td>20mm water</td>
<td>Feb/28/93</td>
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<td></td>
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<td>Nov/1/92</td>
<td>Dec/1/92</td>
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<td>[40 d.a.f]</td>
<td>[70 d.a.f]</td>
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</tr>
<tr>
<td>Cs - Tree and/or shrub savanna (campo sujo)</td>
<td>Sept/15/92</td>
<td>20mm water</td>
<td>20mm water</td>
<td>none</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Oct/29/92</td>
<td>Feb/11/93</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>[44 d.a.f]</td>
<td>[150 d.a.f]</td>
<td></td>
</tr>
<tr>
<td>Cs - Tree and/or shrub savanna (campo sujo)</td>
<td>1991</td>
<td>none</td>
<td>none</td>
<td>Oct/29/92</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&amp; Feb/11/93</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>[1 year a.f]</td>
</tr>
<tr>
<td>Cs - Tree and/or shrub savanna (campo sujo)</td>
<td>1974</td>
<td>none</td>
<td>none</td>
<td>Oct/29/92</td>
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<tr>
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<td></td>
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<td>&amp; Feb/11/93</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>[18 years a.f.]</td>
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d.a.f. = days after fire; Proj.Fogo = joint IBAMA/USForest-Service Project Fire
Table II.4. Treatments* for the Savanna Fertilization Experiment (FertEx)

<table>
<thead>
<tr>
<th>Treatment Plot</th>
<th>Event#1 Jan/10/93</th>
<th>Prescribed Fire Jan/12/93</th>
<th>Event#2 Jan/12/93</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>20mm water</td>
<td>burned well</td>
<td>20mm water</td>
</tr>
<tr>
<td>Nitrate-N</td>
<td>none</td>
<td>burned well</td>
<td>20mm water + 50 kg NaNO₃-N/ha</td>
</tr>
<tr>
<td>Glucose-C</td>
<td>none</td>
<td>burned well</td>
<td>20mm water + 250 kg Glucose-C/ha</td>
</tr>
<tr>
<td>Glucose-C + trate-N</td>
<td>none</td>
<td>burned well</td>
<td>20mm water + 50 kg NaNO₃-N/ha + 250 kg Glucose-C/ha</td>
</tr>
</tbody>
</table>

* Fertilization experiment carried out on Ct - Wooded Savanna; **Last burned before Event#1 in 1989
Table II.5. Crop and treatments for the Agriculture/Pasture Experiment (APEx)

<table>
<thead>
<tr>
<th>Crop</th>
<th>Site Planted in</th>
<th>Episodic Event#1</th>
<th>Episodic Event#2</th>
<th>Single Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn (Zea mays)</td>
<td>Nov/14/92</td>
<td>20mm water Dec/13/92</td>
<td>20mm water Feb/20/93</td>
<td>none</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[29 d.a.p]</td>
<td>[98 d.a.p]</td>
<td></td>
</tr>
<tr>
<td>Soybean (Glycine max)</td>
<td>Nov/14/92</td>
<td>20mm water Dec/20/92</td>
<td>20mm water Feb/21/93</td>
<td>none</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[36 d.a.p]</td>
<td>[99 d.a.p]</td>
<td></td>
</tr>
<tr>
<td>Pasture (Paspalum grass)</td>
<td>Old</td>
<td>20mm water Dec/26/92</td>
<td>none</td>
<td>Feb/23/93</td>
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</tbody>
</table>

d.a.p.= days after planting
Table II.6. Mean N$_2$O Flux Measurements (in g N·ha$^{-1}$·d$^{-1}$) for FScars

<table>
<thead>
<tr>
<th>Type (portuguese name)</th>
<th>Episodic Event#1</th>
<th>Episodic Event#2</th>
<th>Single Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cl - Savanna grassland (campo limpo)</td>
<td>none</td>
<td>none</td>
<td>date 1 0.? (BDL) [Proj.Fogo's Year treatment] none</td>
</tr>
<tr>
<td>Ct - Wooded savanna (cerrado sensu stricto)</td>
<td>-0.3</td>
<td>0.6</td>
<td>0.? (BDL)</td>
</tr>
<tr>
<td>Cd - Savanna woodland (cerrado denso ou Cerradão)</td>
<td>0.7</td>
<td>0.3</td>
<td>0.? (BDL)</td>
</tr>
<tr>
<td>Cs - Tree and/or shrub savanna (campo sujo)</td>
<td>0.2 (BDL)</td>
<td>0.1 (BDL)</td>
<td>none [Proj.Fogo's Control treatment] none</td>
</tr>
</tbody>
</table>

BDL = below flux detection limit of analytical system and measurement technique, which was 0.3 g N$_2$O-N·ha$^{-1}$·d$^{-1}$
Table II.7. Mean N₂O Flux Measurements (in g N·ha⁻¹·d⁻¹) for FertEx

<table>
<thead>
<tr>
<th>Treatment Plot</th>
<th>Episodic Event#1 (Before Fire)</th>
<th>Episodic Event#2 (After Fire)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>0.2 (BDL)</td>
<td>1.8</td>
</tr>
<tr>
<td>Nitrate-N</td>
<td>none</td>
<td>4.3</td>
</tr>
<tr>
<td>Glucose-C</td>
<td>none</td>
<td>1.8</td>
</tr>
<tr>
<td>Glucose-C + trate-N</td>
<td>none</td>
<td>9.1</td>
</tr>
</tbody>
</table>

BDL = below flux detection limit of analytical system and measurement technique, which was 0.3 g N₂O-N·ha⁻¹·d⁻¹.
Table II.8. Mean N₂O Flux Measurements (in g N·ha⁻¹·d⁻¹) for APEX

<table>
<thead>
<tr>
<th>Crop</th>
<th>Episodic Event#1</th>
<th>Episodic Event#2</th>
<th>Single Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn (Zea mays)</td>
<td>3.7</td>
<td>0.6</td>
<td>none</td>
</tr>
<tr>
<td>Soybean (Glycine max)</td>
<td>0.5</td>
<td>1.3</td>
<td>none</td>
</tr>
<tr>
<td>Pasture (Paspalum grass)</td>
<td>0.5</td>
<td>none</td>
<td>0.2 (BDL)</td>
</tr>
</tbody>
</table>

BDL = below flux detection limit of analytical system and measurement technique, which was 0.3 g N₂O-N·ha⁻¹·d⁻¹
Figure II.1. The forest-savanna-grassland ecocline in central Brazil. Modified from Countinho (1990).
Figure II.2.A. FScars soil time-series data for savanna grassland (CI) site. N$_2$O exchange flux with the atmosphere is shown on top of the soil profile, associated with soil gas-phase N$_2$O concentrations. An event refers to the addition of water to the experiment, and includes the subsequent drying period until the next event or until the end of the experiment. The atm. lines indicate ambient N$_2$O mixing ratio (310 ppbv). There are two repetitions for each point/time (dashes). Averages are also shown (circles). Dates shown on the graph correspond to the beginning of the events. Points not connected by lines indicate single measurements for the given date.
Figure II.2.B. FScars soil time-series data for tree/shrub savanna (Cs) site. Other features are the same as for Figure II.2.A.
Figure II.2.C. FScars soil time-series data for wooded savanna (Ct) site. Other features are the same as for Figure II.2.A.
Figure II.2.D. FScars soil time-series data for savanna woodland (Cd) site. Other features are the same as for Figure II.2.A.
Figure II.3.A.  FScars N₂O emissions for tree/shrub savanna (Cs) site. The cumulative curves, or running totals, are integrated summations of interpolated intervals of the minimum sampling period (30 min.) for the entire event period. For a comparison in this site, N₂O fluxes from a control plot not burned since 18 years and other plot burned 1 year before are shown on the upper left corner. E.P.G. means event produced gas. Other features of the flux plots are the same as for Figure II.2.A.
Figure II.3.B.  FScars N$_2$O emissions for wooded savanna (Ct) site. Other features are the same as for Figure II.3.A.
Figure II.3.C. Scenarios N\textsuperscript{O} emissions for savanna woodland (cd) site. Other features are the same as for Figure I.I.3.A.
Figure II.4.A. FertEx soil time-series data for Control treatment. N₂O exchange flux with the atmosphere is shown on top of the soil profile, associated with soil gas-phase N₂O concentrations. An event refers to the addition of water to the experiment, and includes the subsequent drying period until the end of the experiment. The atmospheric lines indicate ambient N₂O mixing ratio (310 ppbv). There are two repetitions for each point/time (dashes). Averages are also shown (circles). Event #1 was carried out on vegetation covered soil, and only for the control treatment.
Savanna
Fertilization

N₂O-N Flux from
Soil (g/ha.day)

Nitrate-N

Soil Depth (cm)

N₂O in the Soil Gas-Phase (ppmv)

Event #1
20 mm water
Area Burned

Event #2
20 mm water + 50 kg/ha Nitrate-N

0.25
0.1
0
-0.1
-0.25
-0.5
-0.75
-1
-1.5
-2
-2.5
-3
-3.5
-4.0

-0.25
-0.5
-0.75
-1
-1.5
-2
-2.5
-3
-3.5
-4.0

0
1
2
3
4
5
6

Time (days)
Figure II.4.C. FertEx soil time-series data for Glucose-C treatment. Other features are the same as for Figure II.4.A.
N₂O-N Flux from Soil (g/ha.day)

<table>
<thead>
<tr>
<th>Event #1</th>
<th>Event #2</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 mm water</td>
<td>20 mm water + 50 kg/ha of Nitrate-N + 250 kg/ha of Glucose-C</td>
</tr>
</tbody>
</table>

**Savanna Fertilization**

**Glucose-C + Nitrate-N**

- Soil Depth (cm)
- N₂O in the Soil Gas-Phase (ppbv)

*Figure II.4.D. FerEx soil time-series data for Nitrate-N + Glucose-C treatment. Other features are the same as for Figure II.4.A.*
Figure II.5.A. FertEx N₂O emissions for Control treatment. The cumulative curves, or running totals, are integrated summations of interpolated intervals of the minimum sampling period (30 min.) for the entire event period. E.P.G. means event produced gas. Other features of the flux plots are the same as for Figure II.4.A.
Savanna Fertilization (flux)  \textit{Nitrate-N}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{savanna_fertilization Flux Nitrate-N.png}
\caption{FertEx N\textsubscript{2}O emissions for Nitrate-N treatment. Other features are the same as for Figure II.5.A.}
\end{figure}
Savanna Fertilization (flux) *Glucose-C*

Figure II.5.C. FertEx N$_2$O emissions for Glucose-C treatment. Other features are the same as for Figure II.5.A.
Savanna Fertilization (flux)  \textit{Nitrate-N + Glucose-C}

\textbf{Figure II.5.D.} FertEx N\textsubscript{2}O emissions for Nitrate-N + Glucose-C treatment. Other features are the same as for Figure II.5.A.
Figure II.6.A. APEx N₂O emissions for Corn (Zea mays) plantation. The cumulative curves, or running totals, are integrated summations of interpolated intervals of the minimum sampling period (30 min.) for the entire event period. E.P.G. means event produced gas. Other features of the flux plots are the same as for Figure II.4.A.
Figure II.6.B. APEx N₂O emissions for Soybean (Glycine max) plantation. Other features are the same as for Figure II.6.A.
Agriculture (flux)  Pasture

Figure II.6.C. APEX N₂O emissions for Pasture (*Paspalum* grass). Other features are the same as for Figure II.6.A.