NASA-TM-109897

NAGW-1826
FINAL
IN-45-CR
OCIT
22285
P-71

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

A.D.Nobre[†], P.M.Crill[‡] and R.C.Harriss[¥]

† Instituto Nacional de Pesquisas da Amazonia
INPA/CPCT/Solos Al. Cosme Ferreira 1756
Manaus AM 69083 BRAZIL

‡ University of New Hampshire
Complex Systems Research Center
Morse Hall Durham NH 03824 USA

¥ National Aeronautics and Space Administration
Mission to Planet Earth
NASA Headquarters Whashington DC USA

- Paper will be submited to *Global Biogeochemical Cycles*

(NASA-TM-109897) EPISODIC NITROUS OXIDE SOIL EMISSIONS IN BRAZILIAN SAVANNA (CERRADO) FIRE-SCARS Final Technical Report (NASA) 71 p

N95-11580

Unclas

G3/45 0022285

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_2O) 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_2O, and the associated profile dynamic of soil-gas-phase N_2O concentrations were studied for several months. Additionally, the effect on episodic emissions of N_2O of nitrate and glucose additions to a cerrado soil after fire and the associated profile dynamic of soil-gas-phase N_2O mixing ratios, was determined. Finally, N_2O episodic emissions in cerrado converted to corn, soybean and pasture fields were investigated during one growing/wet season.

Results showed N_2O consumption/emission for the four fire-scared 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 $N_2O\text{-}N \cdot ha^{-1} \cdot d^{-1}$, respectively. 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.

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

Introduction

Nitrous oxide (N_2O), the third most important anthropogenic greenhouse trace-gas after carbon dioxide (CO_2) and methane (CH_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_2 and CH_4 , for which major global sources are reasonably well known, important atmospheric sources of N_2O 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 km^2 (*Pereira*, 1982), second in area only to the Amazonian rainforest in South America. These frequently burned tropical expanses have become a potentialy important source for greenhouse trace-gas species. On a world wide 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_2O 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_2O would be larger in the wet season (*Hao* et al., 1988). 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_2O emissions in fire-scared cerrado ecosystems during the wet season. Additionally, nitrogen and carbon fertilization experiments were conducted in fire scars, and N_2O 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 Intituto 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_2O 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 álico,* 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_2O emission experiments in this study.

Because N_2O 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 m^2 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 $N \cdot ha^{-1}$ as the first fertilizer treatment, glucose (dextrose, α-D(+) $C_6H_{12}O_6$) at a level of 250 kg $C \cdot ha^{-1}$ as the second treatment, and nitrate at 50 kg $N \cdot ha^{-1}$ plus glucose at 250 kg $C \cdot ha^{-1}$ 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 N_2O flux measurement. The lip of the top was greased lightly with silicon grease (Apiezon) and the collar capped 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 N_2O 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_2O and CO_2 were separated, but only N_2O 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 N_2O that could be detected with this system over a 28-min period at 25°C was 0.3 g $N_2O\text{-}N \cdot ha^{-1} \cdot d^{-1}$.

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 N_2O mixing ratios profiles and N_2O fluxes.

Savanna Grassland (Cl) . At the Cl site, N_2O 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 N_2O 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_2O at this date, given the somewhat strong downward gradient in the soil. Waterlogging induces anaerobiosis, which in turn promotes N_2O reduction to N_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_2O 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 Cl savannas may be a net sink for tropospheric N_2O. But with the highest measured sink-flux only 1 g N_2O-N $\cdot$ $ha^{-1} \cdot d^{-1}$ 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_2O budget.

<u>Tree/shrub</u> <u>savanna</u> (<u>Cs</u>) . Forty three days after fire (29/Oct/92) the N_2O 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_2O 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_2O 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_2O. That can be a corroboration on the inference that N_2O 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_2O-N $\cdot$ ha^{-1} ($\cdot 24h^{-1}$) 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_2O-N · ha^{-1} · d^{-1} before the simulated rainfall (Figure II.3.A). After 20 mm water addition most other flux measurements fell BDL. The soil N_2O 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_2O-N · ha^{-1} · 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_2O 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 N_2O, it very likely would not be from emissions occurring during the main part of the wet season.

Wooded Savanna (Ct). The N_2O 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_2O-N · ha^{-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_2O 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_2O.

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_2O mixing ratios. Nevertheless, for both events and for almost all time-steps, there was a weak upward gradient in soil-gas N_2O 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_2O emission (Figure II.3.C; Table II.6).

The savanna woodland showed that despite weak upward soil N_2O gradients, and a detectable pulse in soil N_2O mixing ratios, fluxes at the soil surface were less than 0.3 g N_2O-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 N_2O emissions.

Cerrado FScars Emissions in Comparison with Emissions in other Similar Ecosystems

Hao et al. (1988) measuring N_2O emissions during the dry season from soils in Gran Sabana ecosystems, Venezuela, found a mean flux from undisturbed plots to be 0.5 g N_2O-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 N_2O fluxes varying from 0.03 to 1 g N_2O-N · ha^{-1} · d^{-1} with an area-average of 0.6 g N_2O-N · ha^{-1} · d^{-1}. *Mosier* et al. (1991) studying two native grasslands in North America found fluxes of 1.8 and 3 g N_2O-N · ha^{-1} · d^{-1}.

The range of values found for N_2O 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_2O 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_2O 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 N_2O during nitrate reduction to N_2. The absence of lags in the pulses throughout the profile corroborates this interpretation, because N_2O 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 N_2O in 24 h, while Event #2, with the ashes from the fire, produced 1.8 g N_2O-N · ha^{-1} in 96 h (0.45 g N_2O-N · ha^{-1} · 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 N_2O 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 N_2O 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 $N_2O\text{-}N \cdot ha^{-1}$ in 96 h (1.1 g $N_2O\text{-}N \cdot ha^{-1} \cdot d^{-1}$) 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 N_2O-N · ha^{-1} in 96 h (0.45 g N_2O-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 N_2O 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_2O-N · ha^{-1} in 96 h (2.3 g N_2O-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 mayz*) . 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 ($(NH_4)_2SO_4$) 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 3.7 g N_2O-N · ha^{-1} 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 0.6 g N_2O-N · ha^{-1} in 24 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 N_2O emissions from fertilized soils, *Eichner* (1990) listed four studies in temperate corn fields for which results ranged from 0.0 to 25.9 g N_2O-N · ha^{-1} · d^{-1}, and averaged of 12 g N_2O-N · ha^{-1} · d^{-1}. *Mosier* and *Hutchinson*, (1981) studying N_2O 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 N_2O-N · ha^{-1} · d^{-1} . They also found that approximately 30 % of the N_2O was emitted during the first two weeks following fertilization, while 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_2O 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_2O. 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_2O production in this soil.

Soybean (*Glycinea 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_2O-N · ha^{-1} in 24 h, 2.6 times more N_2O 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_2 fixed by *Rhizobium* first becomes NH_4, nitrification must proceed before nitrogen substrate is available for denitrification. The fact that water addition depressed N_2O emission, instead of enhancing it as in systems where denitrification is strong, suggests that nitrification is the main pathway for N_2O production in this agroecosystem.

Annual average N_2O emissions measured by *Bremner* et al. (1980), from soybeans fields on six different temperate soils, ranged from 0.9 to 5.4 g $N_2O\text{-}N \cdot ha^{-1} \cdot d^{-1}$. More than ten years ago, *Pereira* (1982) estimated that the approximate nitrogen input to the Brazilian cerrados via fixation in soybean crop fields would be $0.15 \cdot 10^9$ Kg N $\cdot$ yr^{-1} , for a soybean production of about $3 \cdot 10^9$ Kg $\cdot$ yr^{-1} . *Eichner* (1990) estimated total world wide N_2O emissions from fields of cultivated legumes to be 23 to 315 Gg N_2O-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* N_2O-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 N_2O only in those areas fertilized directly by animal urine and feces.

The magnitude of N_2O 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 N_2O 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_2O reported in this paper indicate that water additions do not stimulate intense pulses of N_2O emissions in this soil system.

The data in the N_2O 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_2O 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_2O 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.

Aknowledgment

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.

Bibliography

Adámoli, J., J. Macedo, L. G. Azevedo and J. Madeira Neto, Caracterização da região dos Cerrados, in *Solos dos Cerrados: tecnologias e estrategias de manejo,* vol. edited by W. J. Goedert, pp. Nobel, São Paulo, 1986.

Anderson, I. C., J. S. Levine, M. A. Poth and P. J. Riggan, Enhanced biogenic emissions of nitric oxide and nitrous oxide following surface biomass burning, *JGR, 93,* 3893-3898, 1988.

Anderson, T.-H. and K. H. Domsch, Ratios of microbial biomass carbon to total organic carbon in arable soils, *Soil Biol.Biochem., 21,* 471-479, 1989.

Andreae, G., M. O. Andreae, E. V. Browell, M. Garstang, G. L. Gregory, R. C. Harriss, G. F. Hill, D. J. Jacob, M. C. Pereira, G. W. Sachse, A. W. Setzer, P. L. Silva Dias, R. W. Talbot, A. L. Torres and S. C. Wofsy, Biomass-Burning Emissions and Associated Haze Layers Over Amazonia, *J.Geophy.Res., 93,* 1509-1527, 1988.

Andreae, M. O., The Influence of Tropical Biomass Burning on Climate and the Atmospheric Environment, 1992

Azevedo, L. G. and J. Adámoli, Avaliação agroecológica dos recursos naturais da região dos Cerrados, in *Simpósio sobre o Cerrado*, vol. 6, edited by pp. 729-761, EMBRAPA/CPAC, Brasilia, 1988.

Bowman, A. F., I. Fung, E. Matthews and J. John, Global Analysis of the Potential for N_2O Production in Natural Soils, *Global Biogeochemical Cycles, 7,* 557-597, 1993.

Bremner, J. M., S. G. Robbins and A. M. Blackmer, Seasonal variability in emission of nitrous oxide from soil, *Geophys. Res. Lett., 7,* 641-644, 1980.

Brumme, R. and J. Beese, Effects of liming and nitrogen fertilization on emissions of CO2 and N2O from a temperate forest, *J Geophys Res, 97,* 12851-12858, 1992.

Burton, D. L. and E. G. Beauchamp, Profile Nitrous Oxide and Carbon Dioxide Concentrations in a Soil Subject to Freezing, *Soil Sci.Soc.Am.J., 58,* 115-122, 1994.

Chapin, F. S., P. M. Vitousek and K. Van Clevel, The nature of nutrient limitation in plant communities, *Amer.Naturalist, 127,* 48-58, 1986.

Cicerone, R. J., *Science, 237,* 35-41, 1987.

CODEPLAN, *Atlas do Distrito Federal*, p. 79, Companhia de Desenvolvimento do Planalto Central, Brasilia, 1984.

Coutinho, L. M., Fire in the ecology of the Brazilian cerrado, in *Fire in the Tropical Biota. Ecosystem Processes and Global Challenges*, vol. 84, edited by J. Goldammer, pp. 82-105, Springer-Verlag, Heidelberg, 1990.

Crutzen, P. J., Tropospheric chemical composition measurements in Brazil during the dry season, *J. Atmos. Chem., 2,* 233-256, 1985.

Davidson, E. A., Fluxes of Nitrous Oxide and Nitric Oxide from Terrestrial Ecosystems Ch. 12:, in *Microbial Production and Consumption of Greenhouse Gases: Methane, Nitrogen Oxides, and Halomethanes,* vol. edited by J. E. Rogers and W. B. Whitman, pp. 219-235, American Society for Microbiology, Washington D.C., 1991.

Davidson, E. A., Sources of nitric oxide and nitrous oxide following wetting of dry soil, *Soil Sci.Soc.Amer.J., 56,* 95-102, 1992.

Davidson, E. A., P. A. Matson, P. M. Vitousek, R. Riley, K. Dunkin, G. Garcia-Mendez and J. M. Maass, Processes Regulating Soil Emissions of NO and N2O in a Seasonally Dry Tropical Forest, *Ecology, 74,* 130-139, 1993.

Davidson, E. A., P. M. Vitousek, P. A. Matson, R. Riley, G. Garcia-Mendez and M. Maass, Soil Emissions of Nitric Oxide in a Seasonally Dry Tropical Forest of Mexico, *Journal of Geophysical Research, 96,* 15439-15445, 1991.

Delmas, R., On the emission of carbon, nitrogen, and sulfur in the atmosphere during brushfires in intertropical savanna zones, *Geophys. Res. Lett., 9,* 761-764, 1982.

Dias, B. F. d. S., Manejo e Conservação dos Recursos Naturais Renováveis. Alternativas de desenvolvimento dos Cerrados., 97, 1992.

Dickinson, R. E. and R. J. Cicerone, Review: Future global warming from atmospheric trace gases, *Nature, 319,* 109-115, 1986.

Duxbury, J. M., L. A. Harper and A. R. Mosier, Contributions of Agroecosystems to Global Climate Change, in *Agricultural Ecosystems Effects on Trace Gases and Global Climate Change*, vol. 55, edited by pp. 1-18, American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America, 1993.

Eichner, M. J., Nitrous Oxide Emissions from Fertilized Soils: Summary of Available Data, *J. Environ. Qual., 19,* 272-280, 1990.

Fearnside, P. M., Spatial Concentration of Deforestation in the Brazilian Amazon, *Ambio, 15,* 74-81, 1986.

Firestone, M. K. and E. A. Davidson, Microbial Basis of NO and N2O Production and Consumption in Soil, *Dahlem Workshop on Exchange of Trace Gases between Terrestrial Ecosystems and the Atmosphere, 47,* 1-5, 1989.

Fishman, J., P. Minnis and H. G. J. Reichle, Use of satellite data to study tropospheric ozone in the tropics, *J. Gephys. Res., 91,* 14451-14465, 1986.

Garcia-Mendez, G., J. M. Maass, P. A. Matson and P. M. Vitousek, Nitrogen transformations and nitrous oxide flux in a tropical deciduous forest in Mexico, *Oecologia, 88,* 362-366, 1991.

Goreau, T. J. and W. Z. Mello, Effects of deforestation on sources and sinks of atmospheric carbon dioxide, nitrous oxide, and methane from Central Amazonia soils and biota during the dry season: a preliminary study., *Workshop on Biogeochemistry of Tropical Rain Forests: Problems for Research*, 1987.

Griffiths, R. P., B. A. Caldwell and P. Sollins, Effects of vegetation regime on denitrification potential in two tropical volcanic soils, *Biol. Fertil. Soils, 16,* 157-162, 1993.

Grundmann, G. and D. Rolston, A water function approximation to degree of anaerobiosis associated with denitrification, *Soil Science, 144,* 437-441, 1987.

Hahn, J. and P. J. Crutzen, *Phil.Trans.R.Soc.Lond., B296,* 521-541, 1982.

Hao, W. M., D. Scharffe and P. J. Crutzen, Production of N_2O, CH_4, and CO_2 from Soils in the Tropical Savanna During the Dry Season, *J.Atmos.Chem., 7,* 93-105, 1988.

Hao, W. M., D. Scharffe, J. M. Lobert and P. J. Crutzen, Biomass Burning: An Inportant Source of Atmospheric CO, CO_2 and Hydrocarbons, *Chapman Conference on Global Biomass Burning: Atmospheric, Climatic, and Biospheric Implications*, 19-23, 1990.

Hatshorn, G. S., Plants, in *Costa Rican Natural History*, vol. edited by D. H. Janzen, pp. 118-157, University of Chicago Press, Chicago, 1983.

Huntley, B. J. and B. H. Walker, Ecology of Tropical Savannas, *Ecological Studies*, *42,* 669, 1982.

Hutchinson, G. L. and G. P. Livingston, Use of Chamber Systems to Measure Trace Gas Fluxes, in *Agricultural Ecosystems Effects on Trace Gases and Global Climate Change*, vol. 55, edited by pp. 63-78, American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America, 1993.

Hutchinson, G. L. and A. R. Mosier, Improved soil Cover Method for Field Measurement of Nitrous Oxide Fluxes, *Soil Sci.Soc.Am.J., 45,* 311-316, 1981.

IPCC, Climate Change The IPCC Scientific Assessment, *Intergovernmental Panel on Climate Change*, 1990.

Johnsson, H., L. Klemedtsson, A. Nilsson and B. Svensson, Simulation of field scale denitrification losses from soils under grass ley and barley, *Plant Soil, 138,* 287-302, 1991.

Keeney, D. R. and D. W. Nelson, Nitrogen - Inorganic forms, in *Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties*, vol. edited by A. L. Page, R. H. Miller and D. R. Keeney, pp. 643-709, Agronomy Society of America, Madison, 1982.

Keller, G., M. Keller, W. A. Kaplan, S. C. Wofsy and J. M. d. Costa, Emissions of N_2O From Tropical Forest Soils: Response to Fertilization With NH_4^+, NO_3^-, and PO_4^{-3}, *J.Geophy.Res., 93,* 1600-1604, 1988.

Keller, M., T. J. Goreau, S. C. Wofsy, W. A. Kaplan and M. B. McElroy, Production of Nitrous oxide and consumption of methane by forest soils, *Geophy.Res.Let.,* *10,* 1156-1159, 1983.

Keller, M., W. A. Kaplan and S. C. Wofsy, Emissions of N_2O, CH_4, and CO_2 from tropical forests soils, *J.Geophys.Res.,* *91,* 11791-11802, 1986.

Keller, M. and W. A. Reiners, Soil-Atmosphere exchange of Nitrous Oxide, Nitric Oxide and Methane under Secondary Succession of Pasture to Forest in the Atlantic Lowlands of Costa Rica., *Preliminary Draft,* 29, 1994.

Keller, M., E. Veldkamp, A. M. Weitz and W. A. Reiners, Effect of pasture age on soil trace-gas emissions from a deforested area of Costa Rica, *Nature,* *365,* 244-246, 1993.

Khalil, M. A. K. and R. A. Rasmussen, Increase and seasonal cycles of nitrous oxide in the earth's atmosphere, *Tellus,* *35B,* 161-169, 1983.

Khalil, M. A. K. and R. A. Rasmussen, Nitrous Oxide: Trends and Global mass balance over the last 3000 years, *Annals of Glaciology,* *10,* 9, 1988.

Khalil, M. A. K. and R. A. Rasmussen, The Global Sources of Nitrous Oxide, *J.Geophy.Res.,* *97,* 14651-14660, 1992.

Kim, K.-R. and H. Craig, Nitrogen-15 and Oxygen-18 Characteristics of Nitrous Oxide: A Global Perspective, *Science,* *262,* 1855-1857, 1993.

Lanly, J. P., Tropical Forest Resources, 1982.

Levine, J. S., Introduction, in *Global Biomass Burning: Atmospheric, Climatic, and Biospheric Implications*, vol. edited by J. S. Levine, pp. xxv-xxx, The MIT Press, Cambridge MA, 1991.

Levine, J. S., W. R. CoferIII, E. L. Winstead, S. Sebacher and P. J. Boston, The effects of fire on biogenic soil emissions of nitric oxide and nitrous oxide, *Global Biogeoch.Cycles, 2,* 445-449, 1988.

Li, C., S. Frolking and T. Frolking, A Model of Nitrous Oxide Evolution from Soil Driven by Rainfall Events: 1. Model Structure and Sensitivity, *Journal of Geophysical Research, 97,* 9759-9776, 1992a.

Li, C., S. Frolking and T. Frolking, A Model of Nitrous Oxide Evolution from Soil Driven by Rainfall Events: 2. Model Applications, *Journal of Geophysical Research, 97,* 9777-9783, 1992b.

Livingston, G., G. P. Livingston, P. M. Vitousek and P. A. Matson, Nitrous Oxide Flux and Nitrogen Transformations Across a Landscape Gradient in Amazonia, *J.Geophy.Res., 93,* 1593-1599, 1988.

Lopes, A. S., A survey of the fertility status of soil under "cerrado" vegetation in Brazil, M.S., North Caroline State University, Raleigh, NC, 1975.

Luizão, F., P. Matson, G. Livingston, R. Luizão and P. Vitousek, Nitrous oxide flux following tropical land clearing, *Global Biogeoch. Cycles, 3,* 281-285, 1989.

Matson, P. A. and P. M. Vitousek, Cross-system comparisons of soil nitrogen transformations and nitrous oxide flux in tropical forest ecosystems, *Global Biogeochemical cycles, 1,* 163-170, 1987.

Matson, P. A., P. M. Vitousek, J. J. Ewel, M. J. Mazzarino and G. P. Robertson, Nitrogen transformations following tropical forest felling and burning on a volcanic soil, *Ecology, 68,* 491-502, 1987.

Matson, P. A., P. M. Vitousek, G. P. Livingston and N. A. Swanberg, Sources of Variation in Nitrous Oxide flux from Amazonian Ecosystems, *J.Geophy.Res., 95,* 16,789-16798, 1990.

Matson, P. A., C. Volkmann, K. Coppinger and W. A. Reiners, Annual nitrous oxide flux and soil nitrogen characteristics in sagebrush steppe ecosystems, *Biogeochemistry, 14,* 1-12, 1991.

McElroy, M. B. and S. C. Wofsy, in *Tropical Rain Forests and the World Atmosphere*, vol. edited by G. T. Prance, pp. 36-60, 1986.

Mosier, A. R., W. D. Guenzi and E. E. Schweizer, Soil Losses of Dinitrogen and Nitrous Oxide from Irrigated Crops in Northeastern Colorado, *Soil Sci.Soc.Am.J., 50,* 344-348, 1986.

Mosier, A. R. and G. L. Hutchinson, Nitrous oxide emissions from cropped fields, *J.Environ. Qual., 10,* 169-173, 1981.

Mosier, A. R., D. Schimel, D. Valentine, K. Bronson and W. J. Parton, Methane and nitrous oxide fluxes in native, fertilized and cultivated grasslands, *Nature, 350,* 330-332, 1991.

Instituto Meteorológico Nacional, Catastro de las series de precipitaciones medidas en Costa Rica, 1988.

Nelson, D. W. and L. E. Sommers, Total Carbon, Organic Carbon, and Organic Matter, in *Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties*, vol. edited by A. L. Page, R. H. Miller and D. R. Keeney, pp. 539-579, Agronomy Society of America, Madison, 1982.

Parsons, W. F. J., M. E. Mitre, M. Keller and W. A. Reiners, Nitrate limitation of N_2O production and denitrification from tropical pasture and rain forest soils, *draft,* 20 plus figures, 1993.

Pereira, B. A. d. S., P. P. Furtado, R. C. d. Mendonça and G. I. Rocha, Reserva Ecológica do IBGE (Brasilia - DF): Aspectos Históricos e Fisiográficos, *B.FBCN, 24,* 30-43, 1989.

Pereira, J., Nitrogen Cycling in South American Savannas, *Plant and Soil, 67,* 293-304, 1982.

Prinn, R., D. Cunnold, R. Rasmussen, P. Simmonds, F. Alyea, A. Crawford, P. Fraser and R. Rosen, Atmospheric Emissions and Trends of Nitrous

Oxide Deduced from 10 Years of ALE-GAGE Data, *J.Geophy.Res.*, *95*, 18369-18385, 1990.

Reiners, W. A., A. F. Bowman, W. F. J. Parsons and M. Keller, Tropical Rain Forest Conversion to Pasture: Changes in Vegetation and Soil Properties. Effects of Rain forest Convertion to Pasture, *draft,* 45 plus figures, 1993.

Rice, W. and K. L. Rogers, Denitrification in Subsurface Environments: Potential Source for Atmospheric Nitrous Oxide, in *Agricultural Ecosystems Effects on Trace Gases and Global Climate Change*, vol. 55, edited by pp. 121-132, American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America, 1993.

Robertson, G. P., Fluxes of Nitrous Oxide and Other Nitrogen Trace Gases from Intensively Managed Landscapes: A Global Perspective, in *Agricultural Ecosystems Effects on Trace Gases and Global Climate Change*, vol. 55, edited by pp. 95-108, American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America, 1993.

Robertson, G. P. and J. M. Tiedje, *4th Int.Congr.Ecol.*, 1986.

Robertson, G. P. and J. M. Tiedje, Nitrous Oxide Sources in Aerobic Soils: Nitrification, Denitrification and other biological processes, *Soil.Biol.Biochem.,* *19,* 187-193, 1987.

Rudaz, A., E. A. Davidson and M. K. Firestone, Sources of Nitrous Oxide production following wetting of dry soil, *FEMS Microbiol. Ecol., 85,* 117-124, 1991.

Santos, J. R. d., Biomassa Aérea da Vegetação de Cerrado: Estimativa e Correlação com Dados do Sensor "Thematic Mapper" do Satélite LANDSAT, PhD thesis, Universidade Federal do Paraná, 1988.

Sarmiento, G., The savannas of tropical America, in *Ecosystem of the World: tropical savannas*, vol. 13, edited by pp. 245-288, Elsevier, Amsterdam, 1983.

Schimel, D. S., M. O. Andrea, D. Fowler, I. E. Galbally, R. C. Harriss, D. Ojima, H. Rodhe, T. Rosswall, B. H. Svensson and G. A. Zavarzin, Priorities for an International Research Program on Trace Gas Exchange, *Dahlem Workshop on Exchange of Trace Gases between Terrestrial Ecosystems and the Atmosphere, 47,* 321-331, 1989.

Schimel, D. S., S. Simkins, T. Rosswall, A. R. Mosier and W. J. Parton, 10 Scale and the Measurement of Nitrogen-Gas Fluxes from Terrestrial Ecosystems, *Workshop on Spatial and Temporal Variability of Biospheric and Geospheric Processes: Research Needed to determine Interactions with Global environmental Change, 35,* 179-192, 1988.

Schuster, M. and R. Conrad, Metabolism of nitric oxide and nitrous oxide during nitrification and denitrification in soil at different incubations conditions, *FEMS Microbiol. Ecol., 101,* 133-143, 1992.

Seiler, W. and R. Conrad, Cp 9: Contribution of Tropical Ecosystems to the Global Budgets of Trace Gases, Especially CH4, H2, CO, and N2O, *The Geophysiology of Amazonia Vegetation and Climate interactions - International Conference on Climatic, Biotic, and Human interactions in the Humid Tropics* , 133-162, 1987.

Sexstone, A. J., T. B. Parkin and J. M. Tiedje, Temporal Response of Soil Denitrification Rates to Rainfall and Irrigation, *Soil Sci.Soc.Am.J., 49,* 99-103, 1985.

Singh, H. B., *Evir.Sci.Technol., 21,* 320-327, 1987.

Skole, D. L. and C. J. Tucker, Tropical deforestation, habitat fragmentation, and adversely affected habitat in the Brazilian Amazon, 1978-1988, *Science,* 1993.

Smith, K. A. and J. R. M. Arah, Losses of nitrogen by denitrification and emissions of nitrogen oxides from soils, *The Fertilizer Society, 299,* 35, 1990.

Sollins, P., F. Sancho, R. Mata and R. L. Sanford, Soils and Soils Research, in *La Selva: Ecology and natural history of a neotropical rainforest,* vol. edited by L. McDade, K. Bawa, H. Hespenheide and G. Hartshorn, pp. University of Chicago Press, Chicago, 1993.

Suhet, A. R. and K. D. Ritchey, Nitrate Leaching in Cerrado Soil, 1981.

Tamm, C. O., *Nitrogen in Terrestrial Ecosystems. Questions of productivity, vegetational changes, and ecosystem stability, Ecological Studies,* p. 116, Springer-Verlag, Berlin, 1991.

Terry, R. E., R. L. I. Tate and J. M. Duxbury, Nitrous Oxide Emissions from Drained, Cultivated Organic Soils of South Florida, *J. of the Air Pollution Control Association, 31,* 1173-1176, 1981.

USDA, Soil Taxonomy. A basic system of soil classification for making and interpreting soil surveys, *Agriculture Handbook, 436,* 754, 1975.

Vitousek, P. M. and P. A. Matson, Nitrogen tranformations in a range of tropical forest soils, *Soil biol. Biochem., 20,* 361-367, 1988.

Vitousek, P. M. and P. A. Matson, Agriculture, the Global Nitrogen Cycle, and Trace Gas Flux, in *Biogeochemistry of Global Change,* vol. Tenth International Symposium on Environmental Biogeochemistry (ISEB), edited by R. S. Oremland, pp. 193-208, Chapman & Hall, San Francisco, 1993.

Vitousek, P. M. and R. L. J. Sanford, Nutrient Cycling in Moist Tropical Forest, *Ann.Rev.Ecol.Syst., 17,* 137-167, 1986.

Weier, K. L., I. C. Macrae and R. J. K. Myers, Seasonal Variation in Denitrification in a Clay Soil Under a Cultivated Crop and Permanent Pasture, *Soil Biol. Biochem., 23,* 629-635, 1991.

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

Abbreviation - Type (*portuguese name*)	**Area** in 1000 km² (*% of total for the biome*)	**Density** trees/ha	**Tree canopy cover** %
Cl- **Savanna grassland** (*campo limpo*)	112 (*5.5*)	0	0
Cs - **Tree and/or shrub savanna** (*campo sujo*)	236 (*11.6*)	500	< 2
Ct - **Wooded savanna** (*cerrado sensu stricto*)	1080 (*53.0*)	1000	2 - 15
Cd - **Savanna woodland** (*cerrado denso ou Cerradão*)	169 (*8.3*)	3000	15 - 40

* from *Sarmiento* (1983) and *Azevedo & Adámoli* (1988)

Table II.2. Main superficial soil properties for the savannas in central Brazil*

Soil Parameter	Vegetation Type *(portuguese name)*			
	Ct - **Savanna grassland** *(campo limpo)*	Cs - **Tree/shrub savanna** *(campo sujo)*	Ct - **Wooded savanna** *(cerrado sensu stricto)*	Cd - **Savanna woodland** *(cerrado denso)*
Clay (%)	33	36	34	32
Silt (%)	20	16	15	16
Sand (%)	46	18	51	53
pH (H_2O)	4.9	4.9	5.0	5.1
Organic C (%)	2.2	2.3	2.4	2.3
CEC (meq%)	1.1	1.2	1.4	1.8
Al_3^+ (meq%)	0.7	0.6	0.7	0.6
Al_3^+ Sat. (%)	66	58	54	44
Ca (meq%)	0.2	0.3	0.5	0.7
Mg (meq%)	0.7	0.1	0.2	0.4
K (meq%)	0.1	0.1	0.1	0.1
P (ppm)	0.5	0.5	0.9	2.1
Zn (ppm)	0.6	0.6	0.7	0.7
Cu (ppm)	0.6	0.8	0.9	1.3
Mn (ppm)	5.4	10.3	15.9	22.9

* 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)

Abbreviation - Type *(portuguese name)*	**Site's Last Fire in**	**Episodic Event#1**	**Episodic Event#2**	**Single Measurements**
Cl - **Savanna grassland** *(campo limpo)*	Sept/21/92	none	20mm water Feb/18/93 [150 d.a.f]	Nov/15/92 [55 d.a.f]
Ct - **Wooded savanna** *(cerrado sensu stricto)*	Sept/16/92	20mm water Nov/9/92 [55 d.a.f]	20mm water Dec/8/92 [84 d.a.f]	Feb/28/93 [166 d.a.f]
Cd - **Savanna woodland** *(cerrado denso ou Cerradão)*	Sept/23/92	20mm water Nov/1/92 [40 d.a.f]	20mm water Dec/1/92 [70 d.a.f]	Feb/28/93 [158 d.a.f]
Cs - **Tree and/or shrub savanna** *(campo sujo)*	Sept/15/92	20mm water Oct/29/92 [44 d.a.f]	20mm water Feb/11/93 [150 d.a.f]	none
Cs - **Tree and/or shrub savanna** *(campo sujo)* [Proj.Fogo's *Year* treatment]	1991	none	none	Oct/29/92 & Feb/11/93 [1 year a.f]
Cs - **Tree and/or shrub savanna** *(campo sujo)* [Proj.Fogo's *Control* treatment]	1974	none	none	Oct/29/92 & Feb/11/93 [18 years a.f.]

d.a.f.= days after fire; Proj.Fogo = joint IBAMA/USForest-Service Project Fire

Table II.4. Treatments* for the Savanna Fertilization Experiment (FertEx)

Treatment Plot	Event#1** Jan/10/93	Prescribed Fire Jan/12/93	Event#2 Jan/12/93
Control	20mm water	burned well	20mm water
Nitrate-N	none	burned well	20mm water + 50 kg $NaNO_3$-**N**/ha
Glucose-C	none	burned well	20mm water + 250 kg Glucose-**C**/ha
Glucose-C + trate-N	none	burned well	20mm water + 50 kg $NaNO_3$-**N**/ha + 250 kg Glucose-**C**/ha

* 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)

Crop	Site Planted in	Episodic Event#1	Episodic Event#2	Single Measurement
Corn *(Zea mayz)*	Nov/14/92	20mm water Dec/13/92 [29 d.a.p]	20mm water Feb/20/93 [98 d.a.p]	none
Soybean *(Glycinea max)*	Nov/14/92	20mm water Dec/20/92 [36 d.a.p]	20mm water Feb/21/93 [99 d.a.p]	none
Pasture *(Paspalum grass)*	Old	20mm water Dec/26/92	none	Feb/23/93

d.a.p.= days after planting

Table II.6. Mean N_2O Flux Measurements (in g **N**$\cdot ha^{-1} \cdot d^{-1}$) for FScars

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

BDL = below flux detection limit of analytical system and measurement technique, which was 0.3 g N_2O-**N**$\cdot ha^{-1} \cdot d^{-1}$

Table II.7. Mean N_2O Flux Measurements (in g $\mathbf{N} \cdot ha^{-1} \cdot d^{-1}$) for FertEx

Treatment Plot	Episodic Event#1 (Before Fire)	Episodic Event#2 (After Fire)
Control	0.? (BDL)	1.8
Nitrate-N	none	4.3
Glucose-C	none	1.8
Glucose-C + trate-N	none	9.1

BDL = below flux detection limit of analytical system and measurement technique, which was 0.3 g $\mathbf{N_2O}$-$\mathbf{N} \cdot ha^{-1} \cdot d^{-1}$

Table II.8. Mean N_2O Flux Measurements (in g $\mathbf{N} \cdot ha^{-1} \cdot d^{-1}$) for APEx

Crop	Episodic Event#1	Episodic Event#2	Single Measurement
Corn ***(Zea mayz)***	3.7	0.6	none
Soybean ***(Glycinea max)***	0.5	1.3	none
Pasture ***(Paspalum grass)***	0.5	none	0.? (BDL)

BDL = below flux detection limit of analytical system and measurement technique, which was 0.3 g $\mathbf{N_2O\text{-}N} \cdot ha^{-1} \cdot d^{-1}$

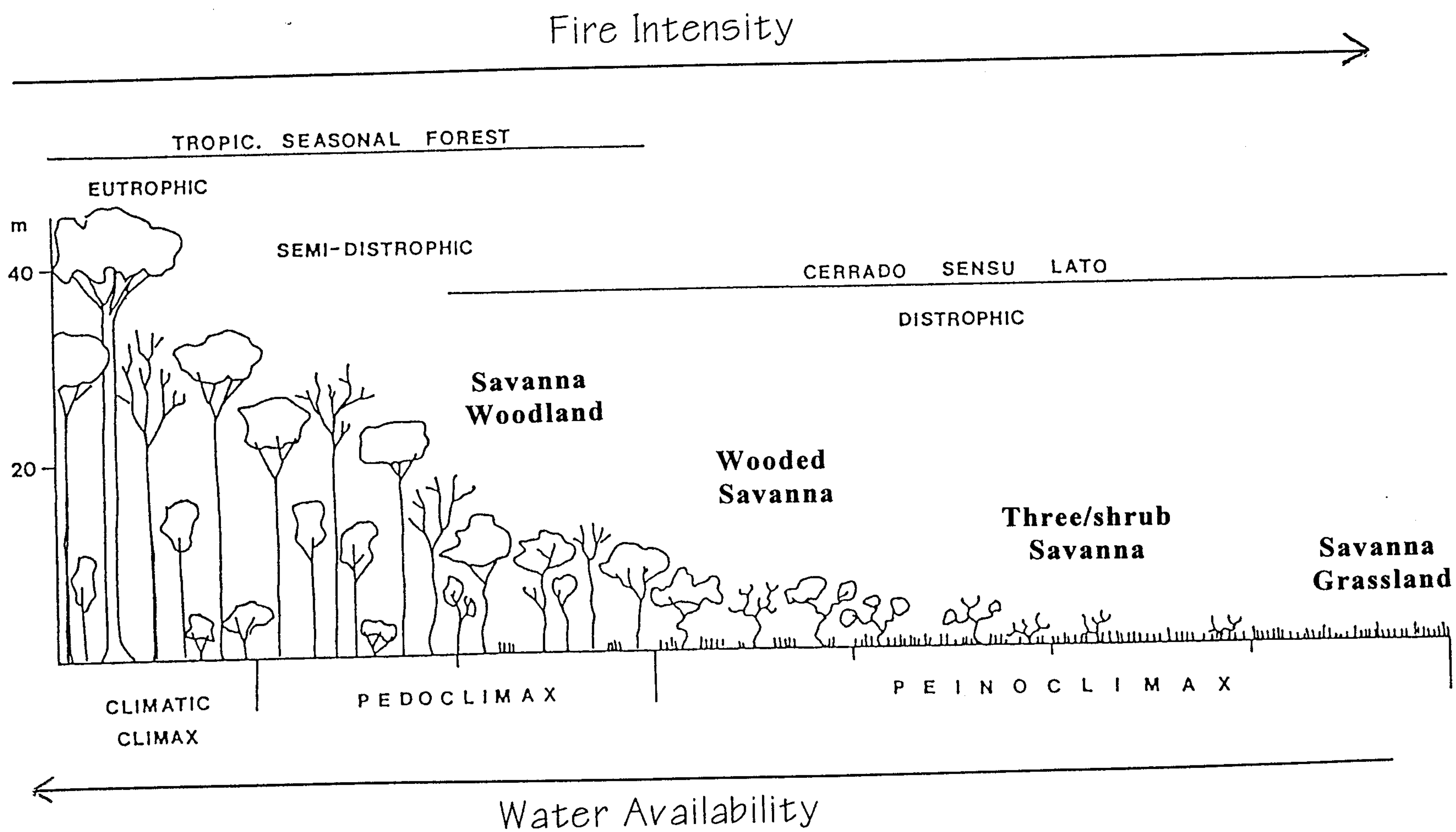

Figure II.1. The forest-savanna-grassland ecocline in central Brazil. Modified from *Countinho* (1990).

Savanna Grassland *Cl*

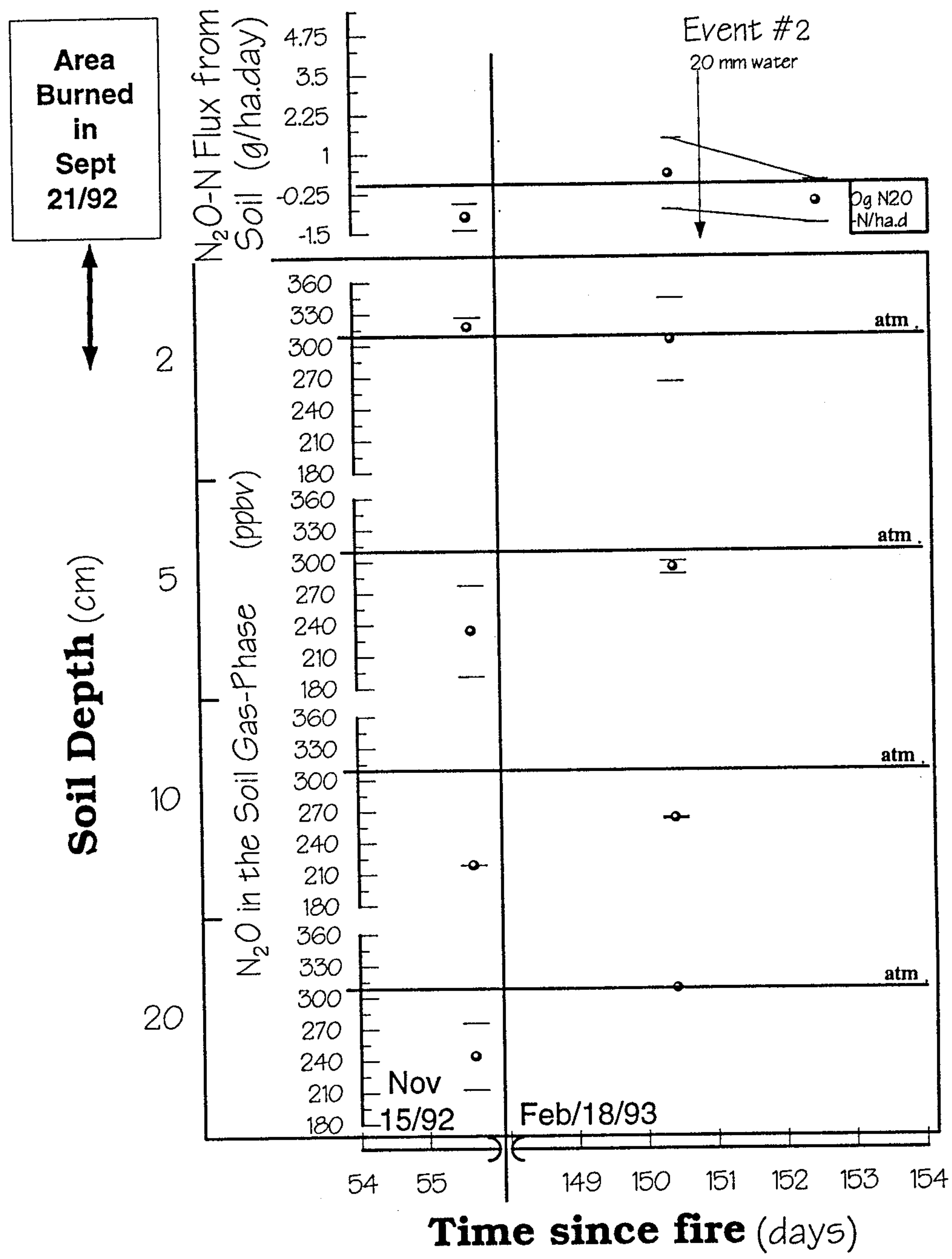

Figure II.2.A. FScars soil time-series data for savanna grassland (Cl) site. N_2O exchange flux with the atmosphere is shown on top of the soil profile, associated with soil gas-phase N_2O concentrations. An event refers to the addition of water to the experiment, and includes the subsequent drying period until the next event or until the end of the experiment. The atm. lines indicate ambient N_2O 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 beggining of the events. Points not connected by lines indicate single measurements for the given date.

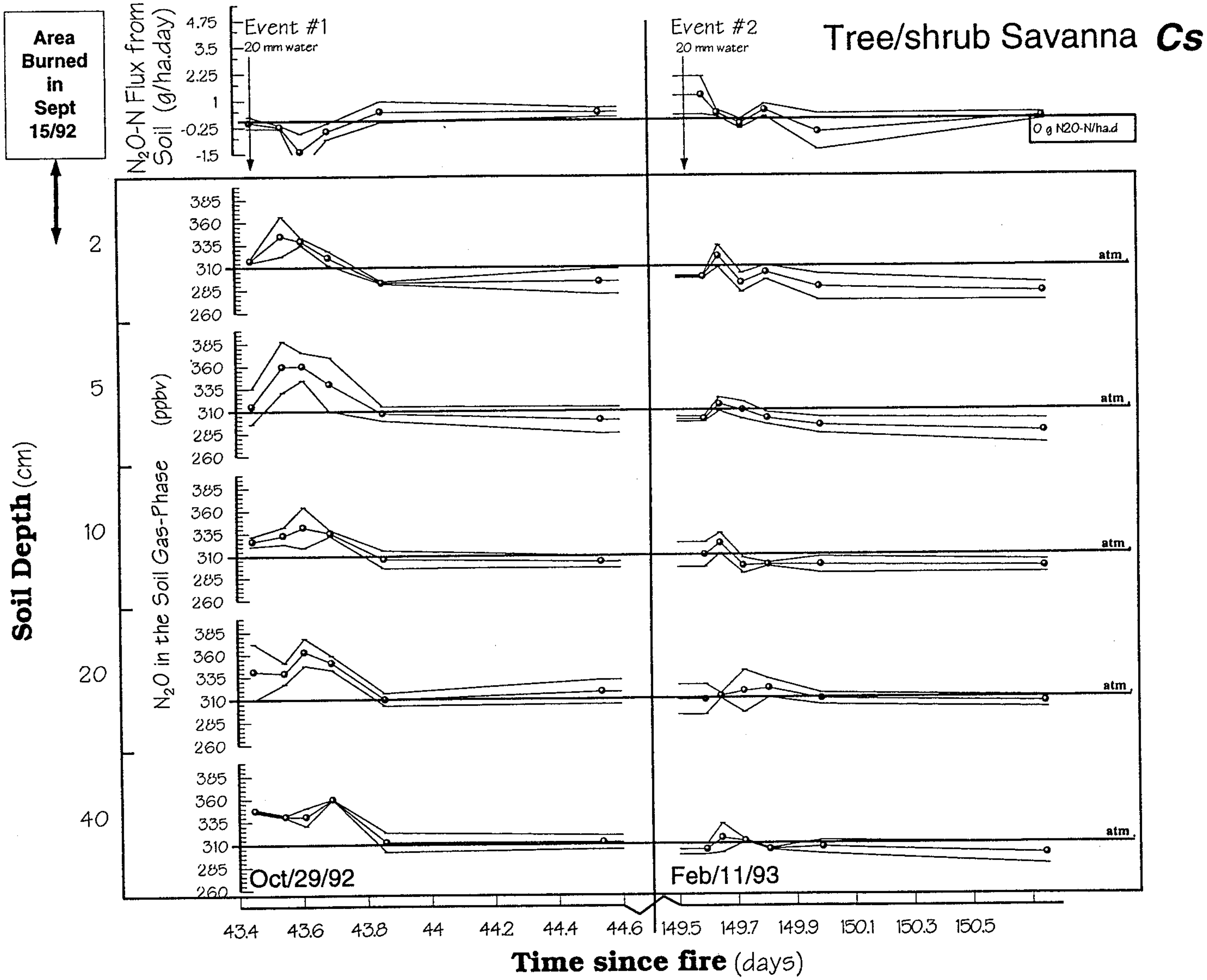

Figure II.2.B. FScars soil time-series data for tree/shrub savanna (Cs) site. Other features are the same as for Figure II.2.A.

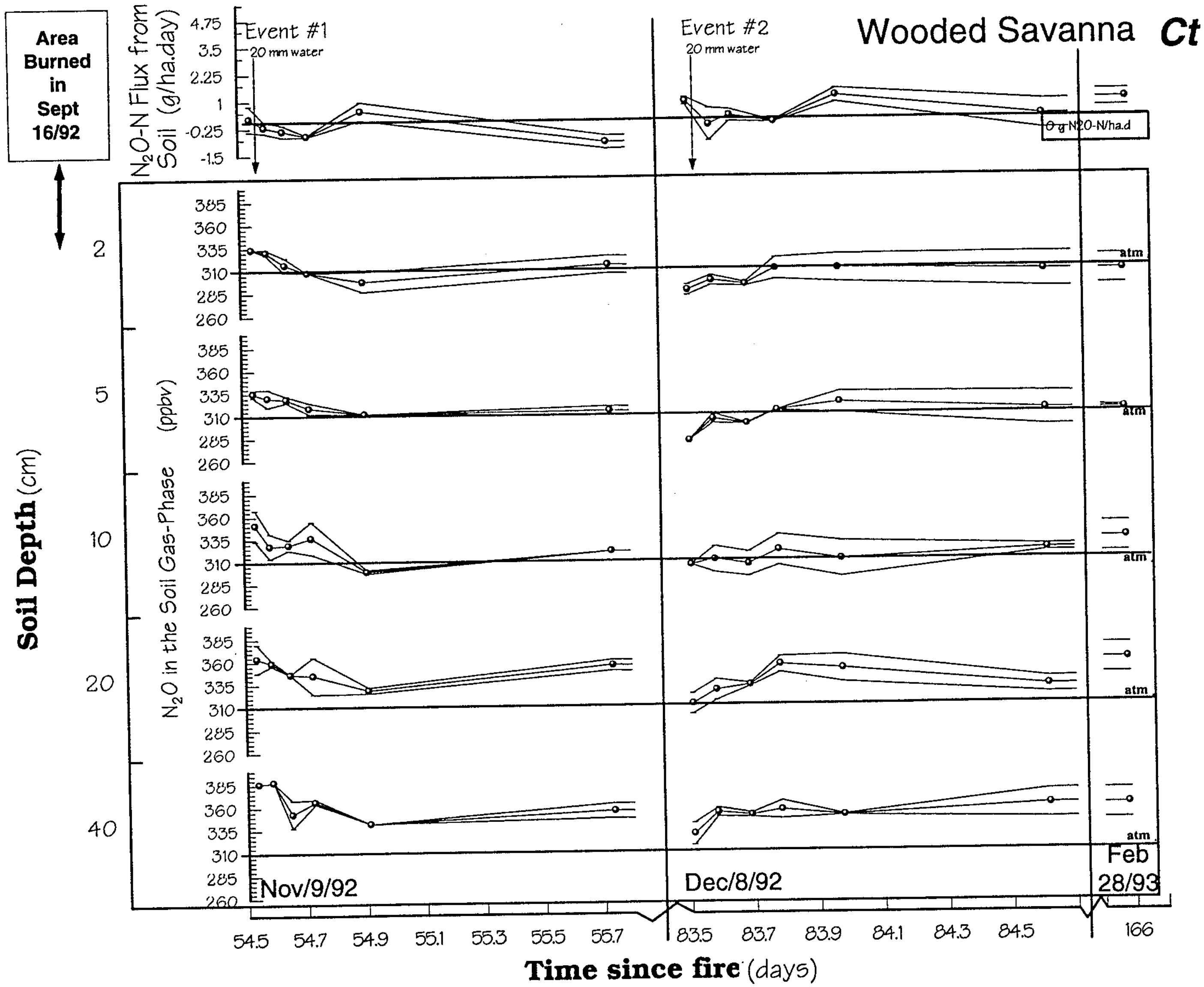

Figure II.2.C. FScars soil time-series data for wooded savanna (Ct) site. Other features are the same as for Figure II.2.A.

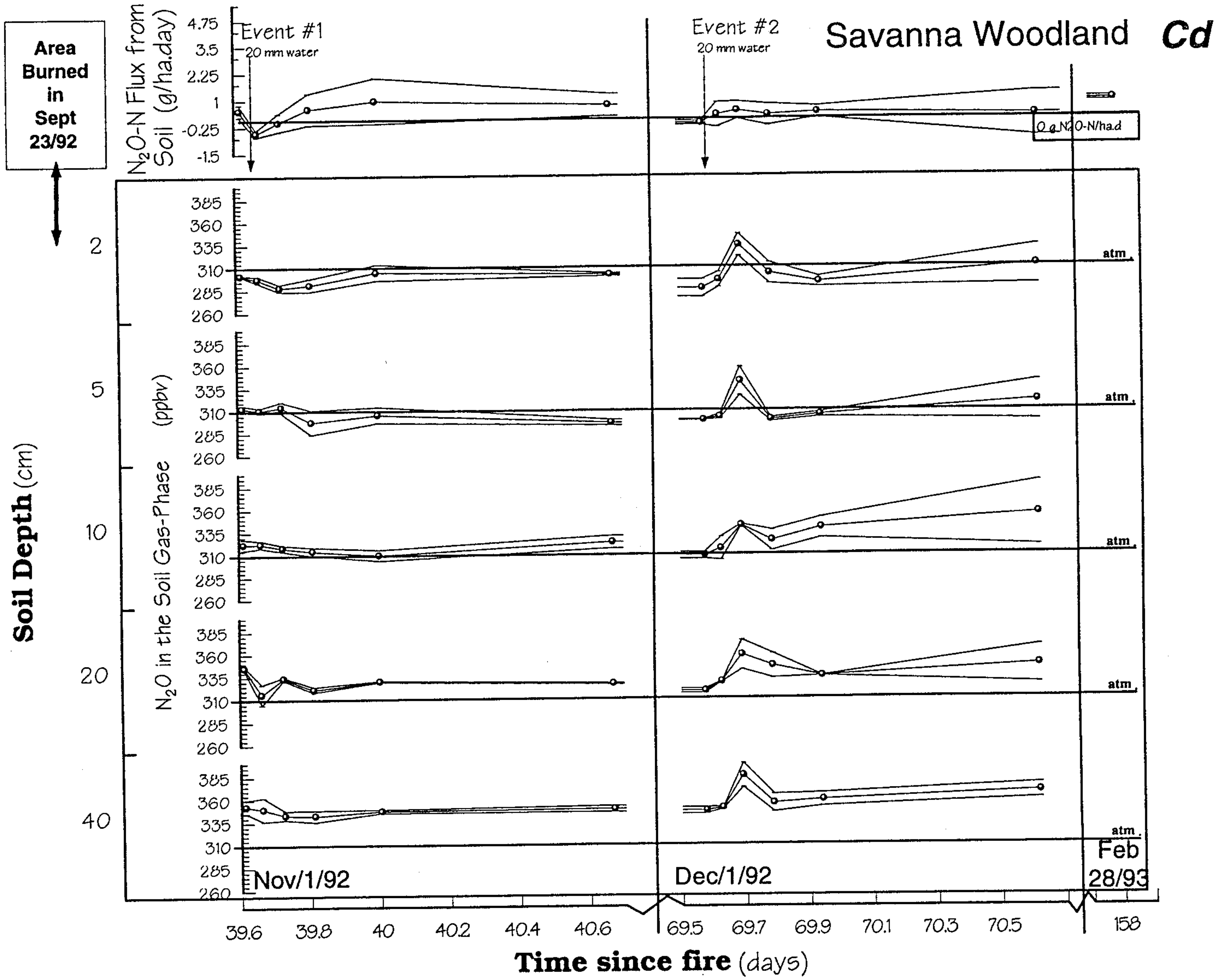

Figure II.2.D. FScars soil time-series data for savanna woodland (Cd) site. Other features are the same as for Figure II.2.A.

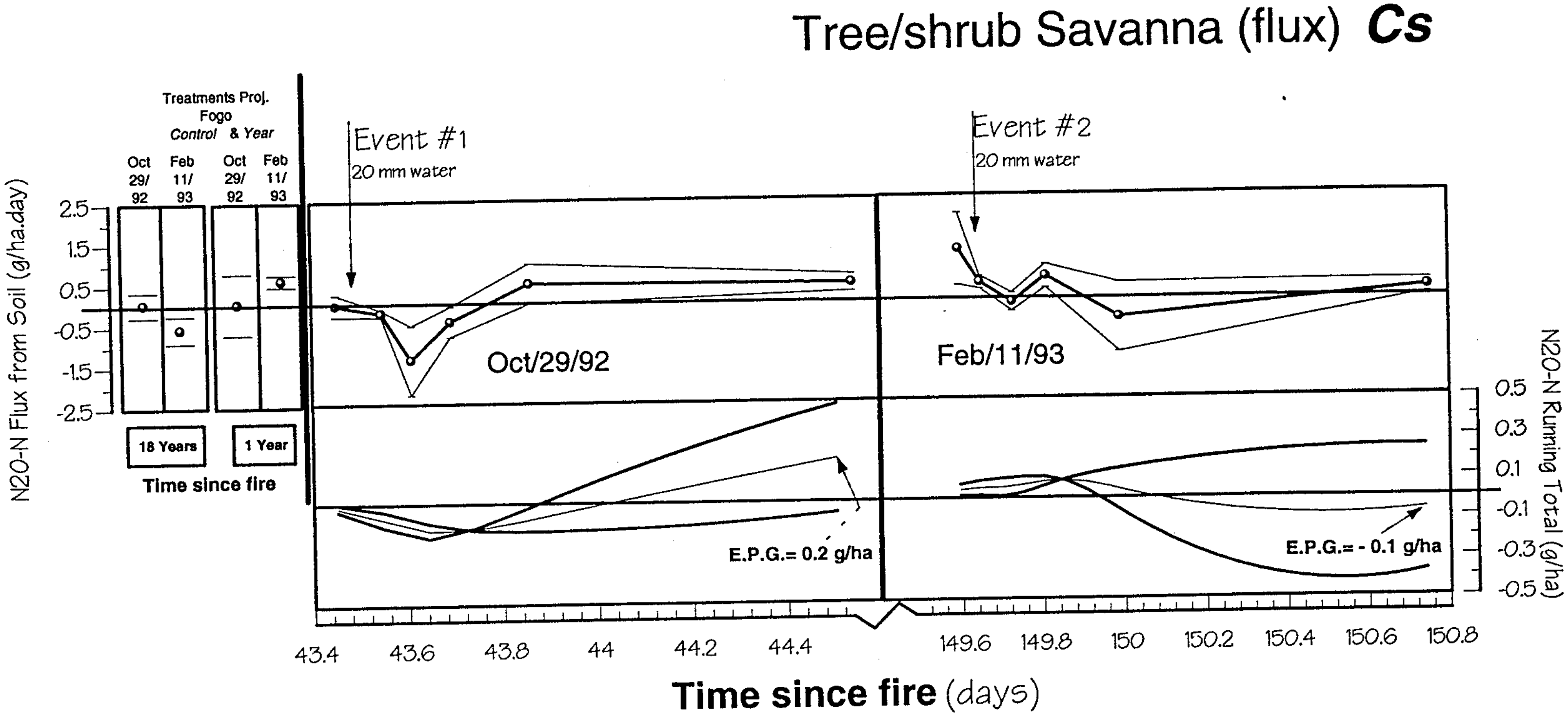

Figure II.3.A. FScars N_2O emissions for tree/shrub savanna (Cs) site. The cumulative curves, or running totals, are integrated summations of interpolated intervals of the minimum sampling period (30 min.) for the entire event period. For a comparisson in this site, N_2O fluxes from a control plot not 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.

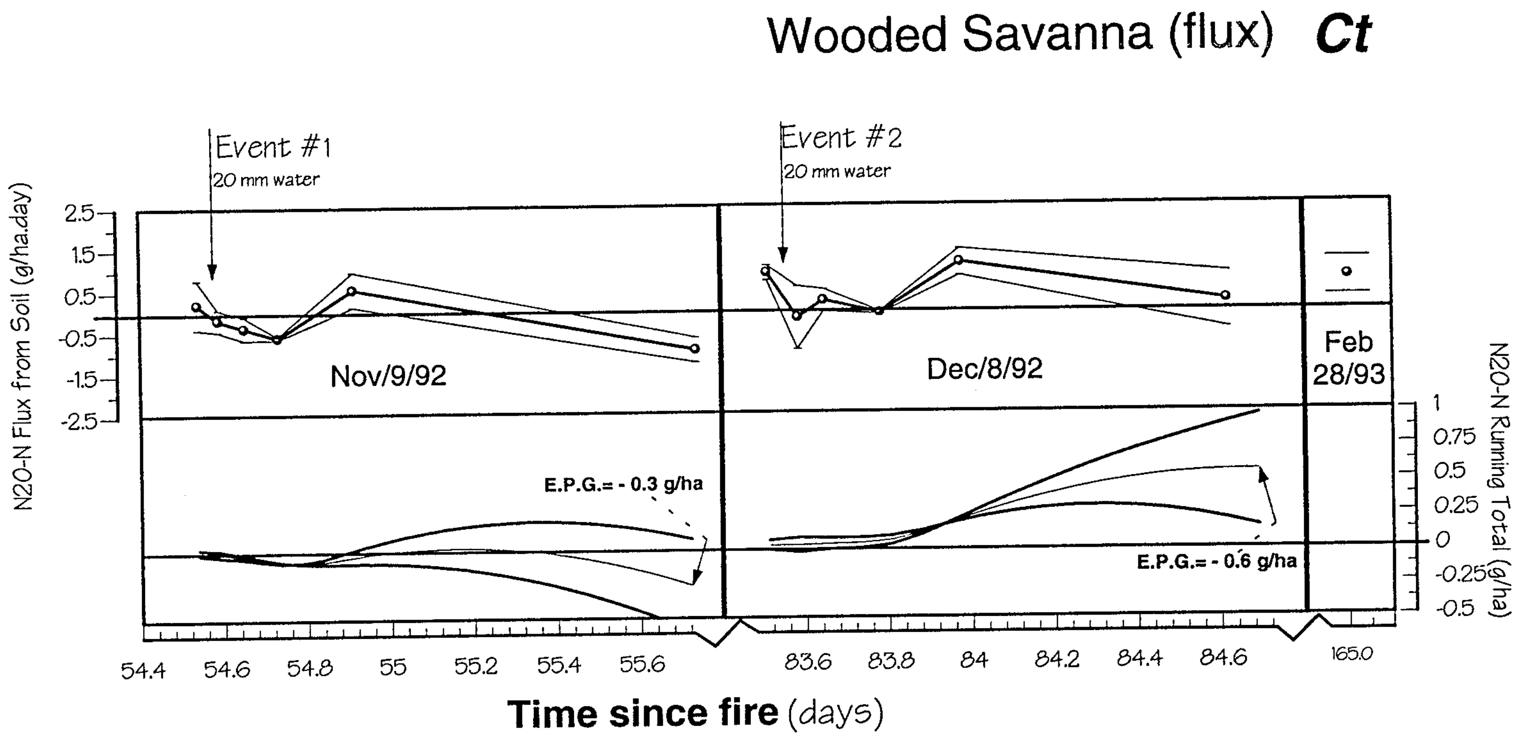

Figure II.3.B. FScars N_2O emissions for wooded savanna (Ct) site. Other features are the same as for Figure II.3.A.

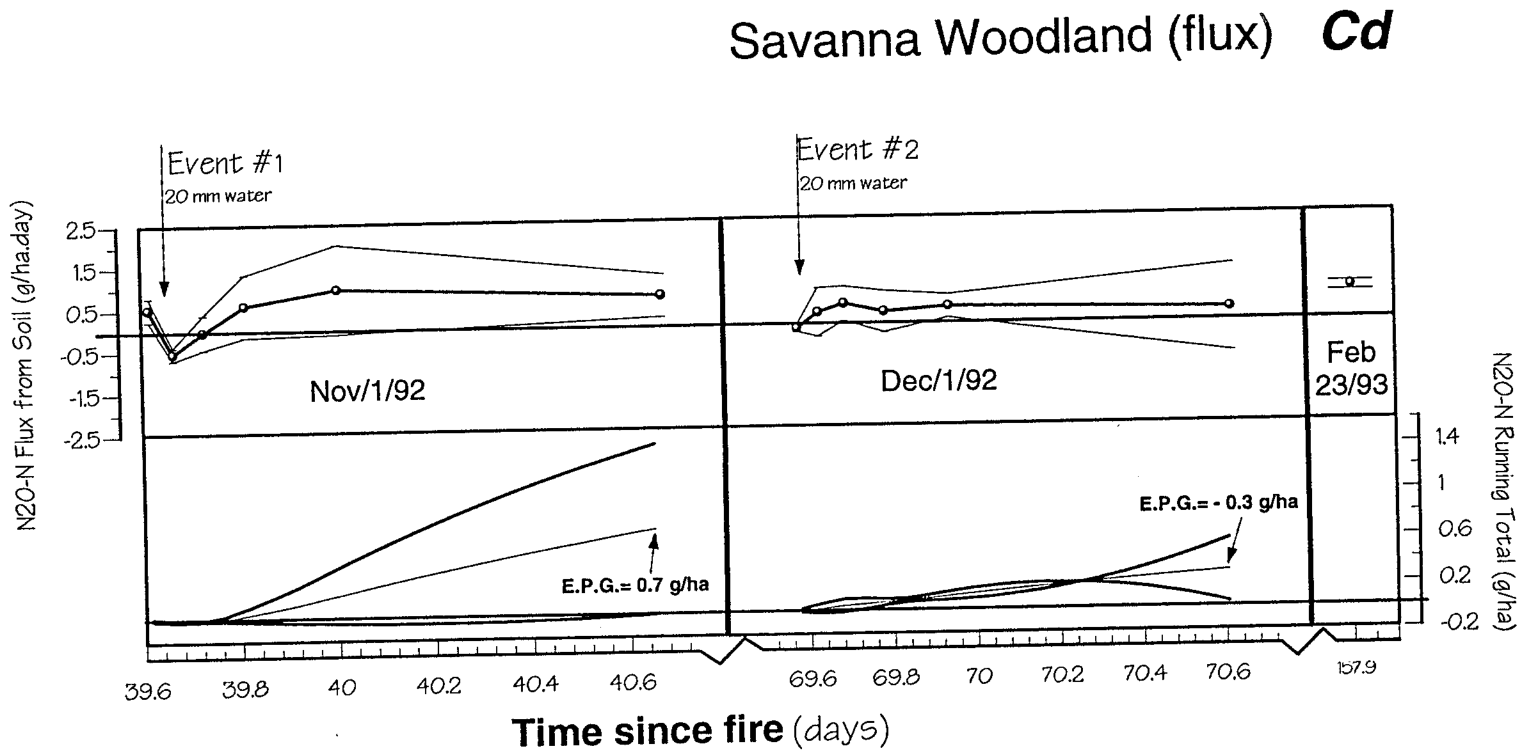

Figure II.3.C. FScars N_2O emissions for savanna woodland (Cd) site. Other features are the same as for Figure II.3.A.

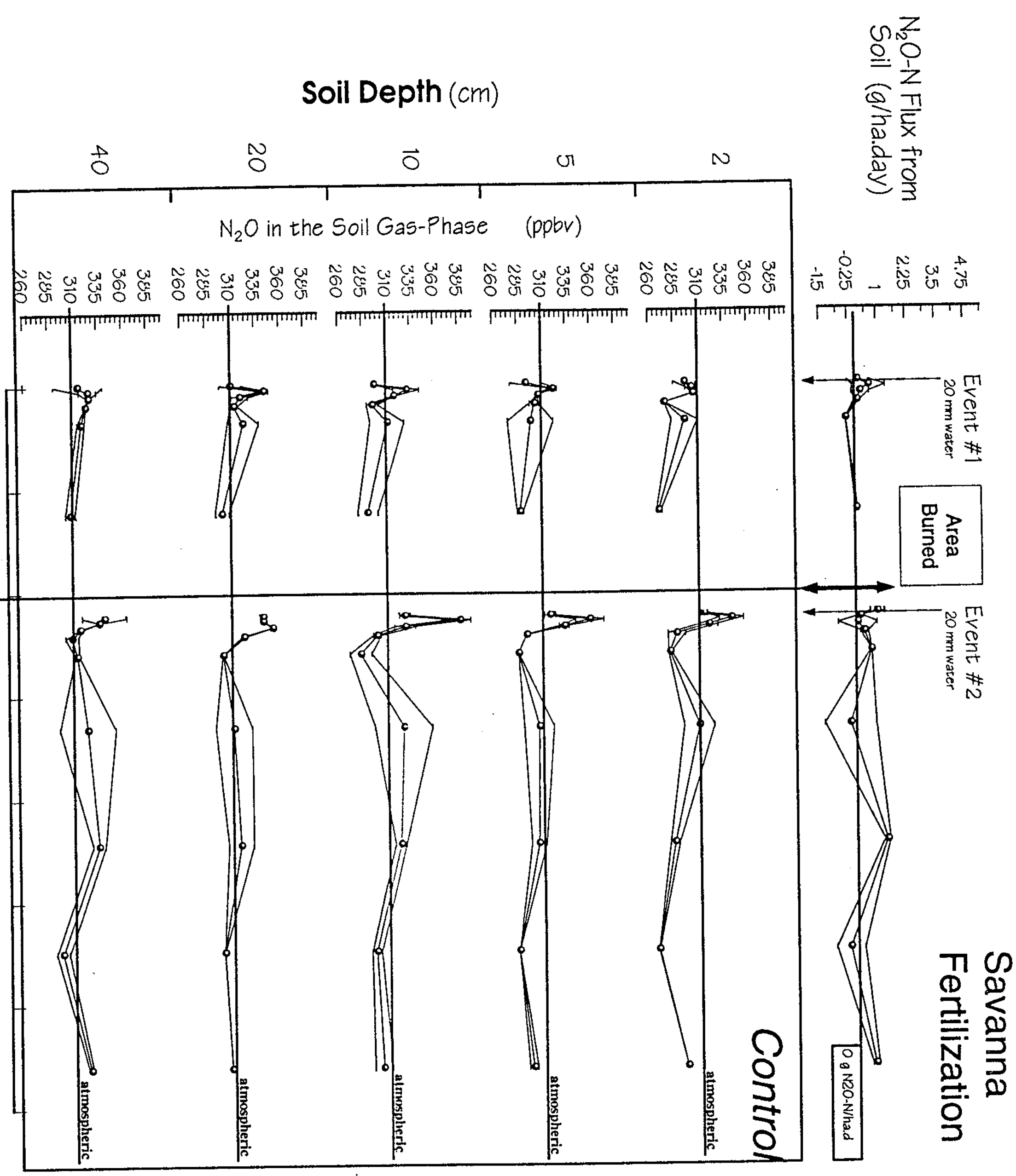

Figure II.4.A. FertEx soil time-series data for Control treatment. N_2O exchange flux with the atmosphere is shown on top of the soil profile, associated with soil gas-phase N_2O concentrations. An event refers to the addition of water to the experiment, and includes the subsequent drying period until the end of the experiment. The atmospheric lines indicate ambient N_2O 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.

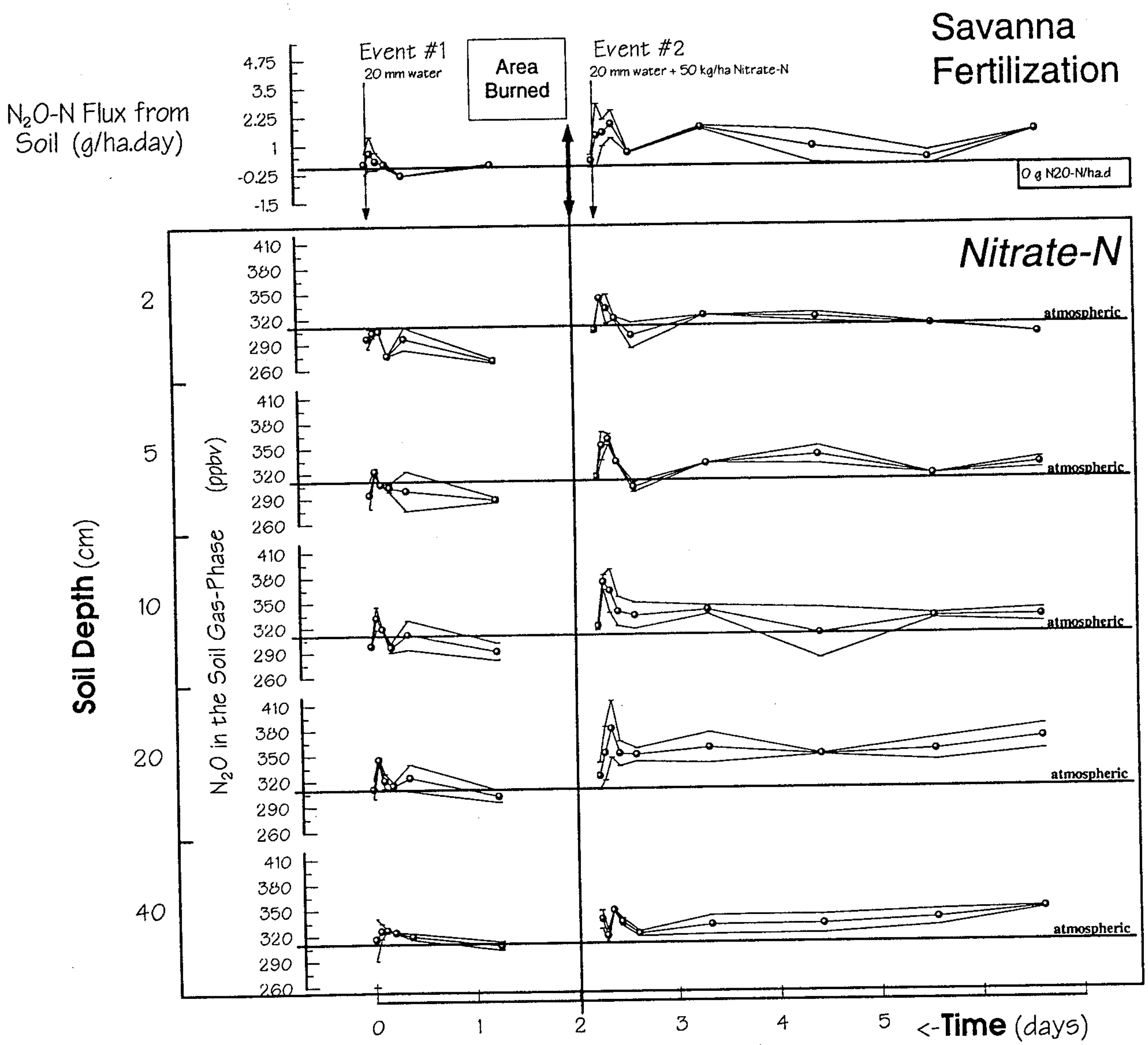

Figure II.4.B. FertEx soil time-series data for Nitrate-N treatment. Other features are the same as for Figure II.4.A.

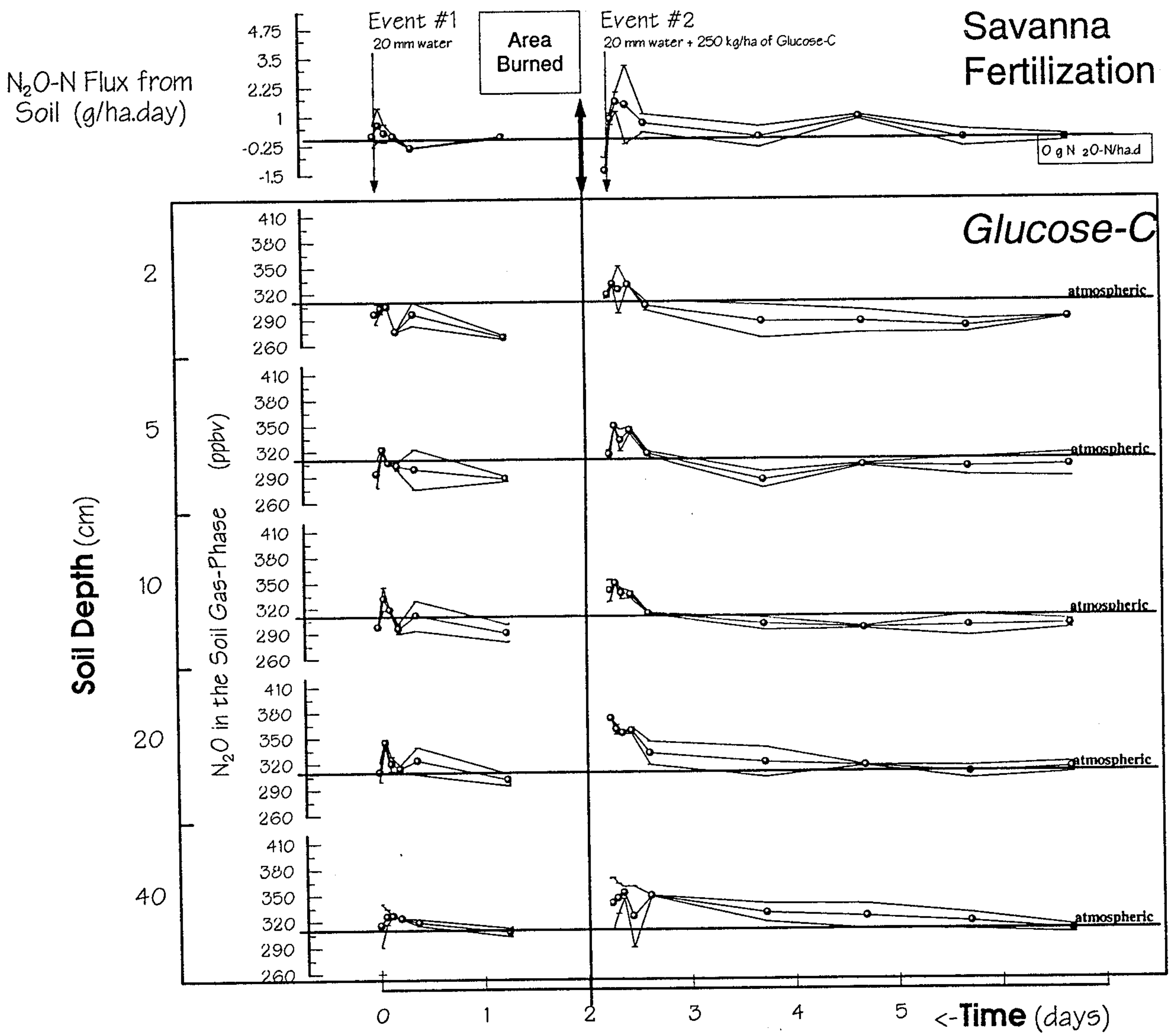

Figure II.4.C. FertEx soil time-series data for Glucose-C treatment. Other features are the same as for Figure II.4.A.

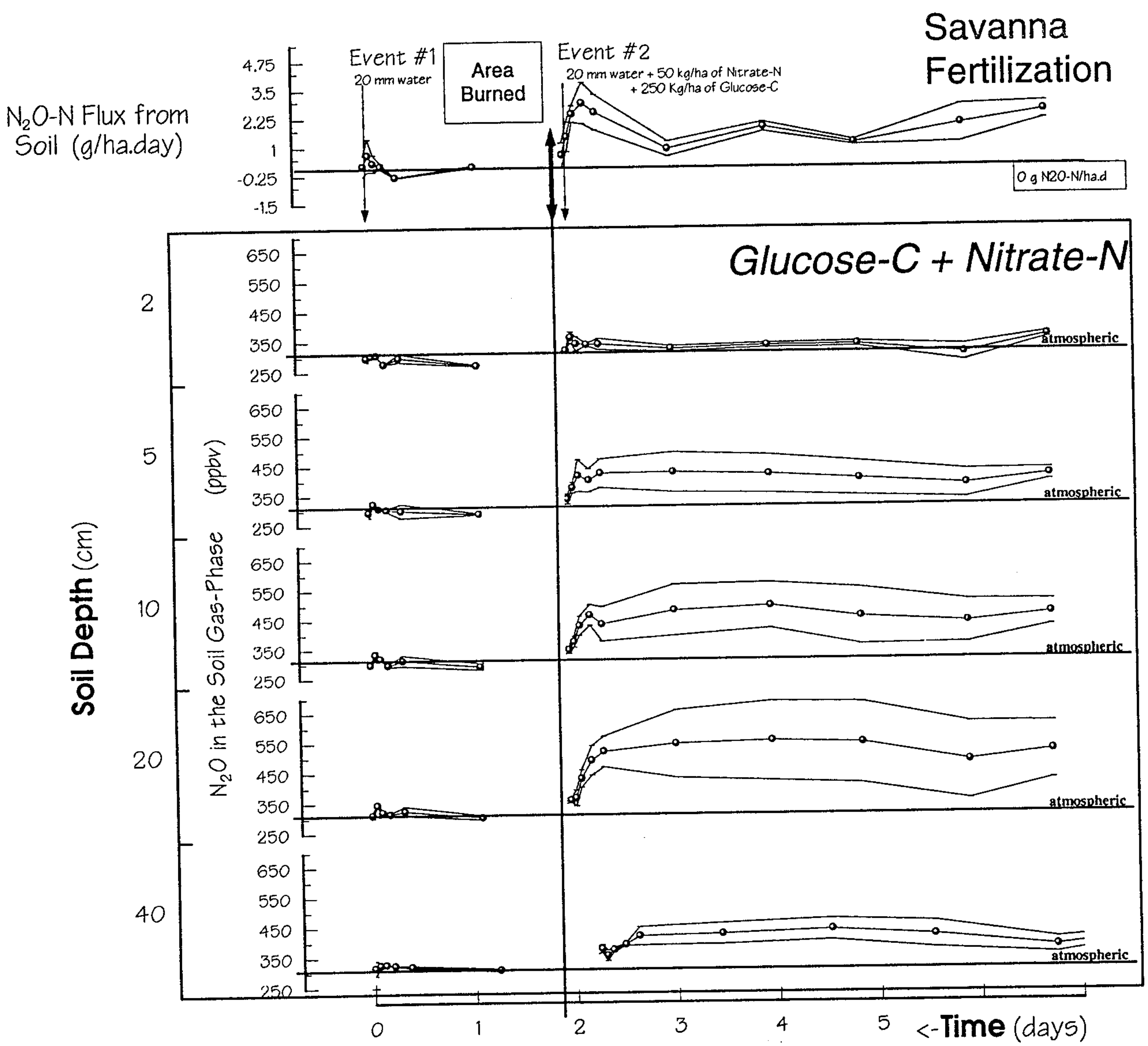

Figure II.4.D. FertEx soil time-series data for Nitrate-N + Glucose-C treatment. Other features are the same as for Figure II.4.A.

Savanna Fertilization (flux) ***Control***

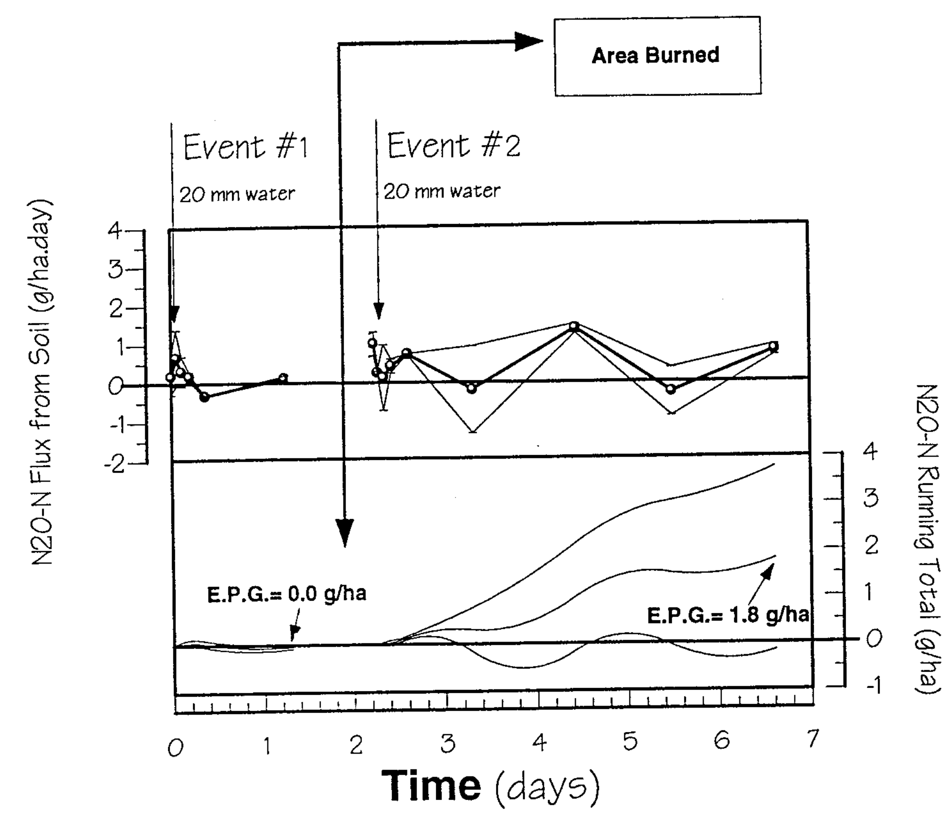

Figure II.5.A. FertEx N_2O emissions for Control treatment. The cumulative curves, or running totals, are integrated summations of interpolated intervals of the minimum sampling period (30 min.) for the entire event period. E.P.G. means event produced gas. Other features of the flux plots are the same as for Figure II.4.A.

Savanna Fertilization (flux) ***Nitrate-N***

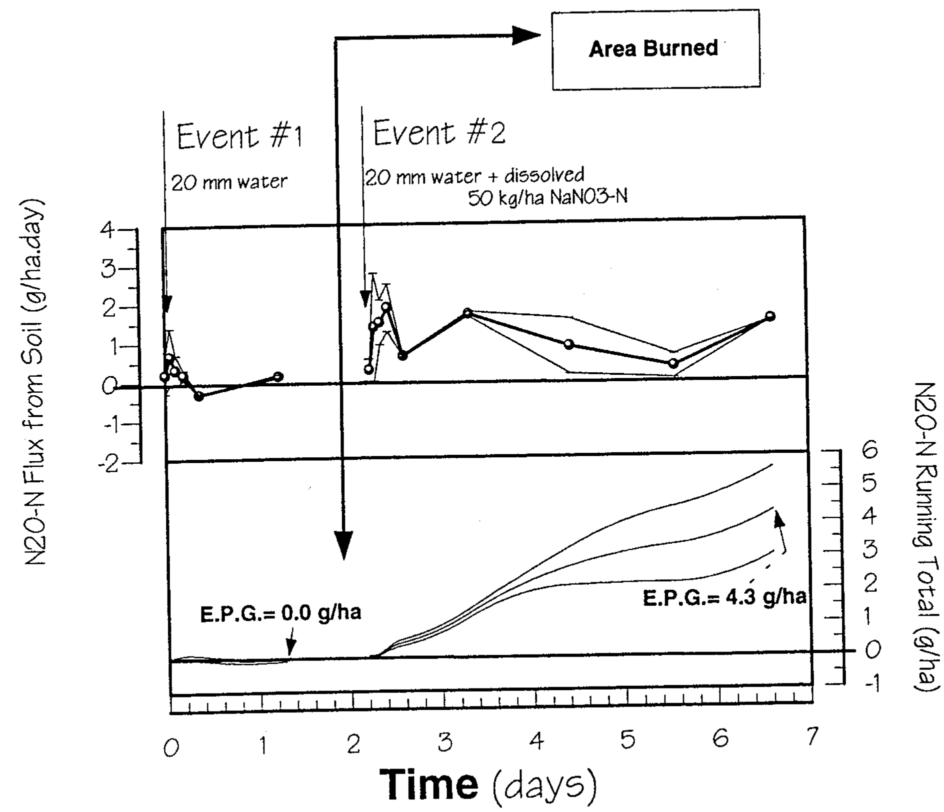

Figure II.5.B. FertEx N_2O emissions for Nitrate-N treatment. Other features are the same as for Figure II.5.A.

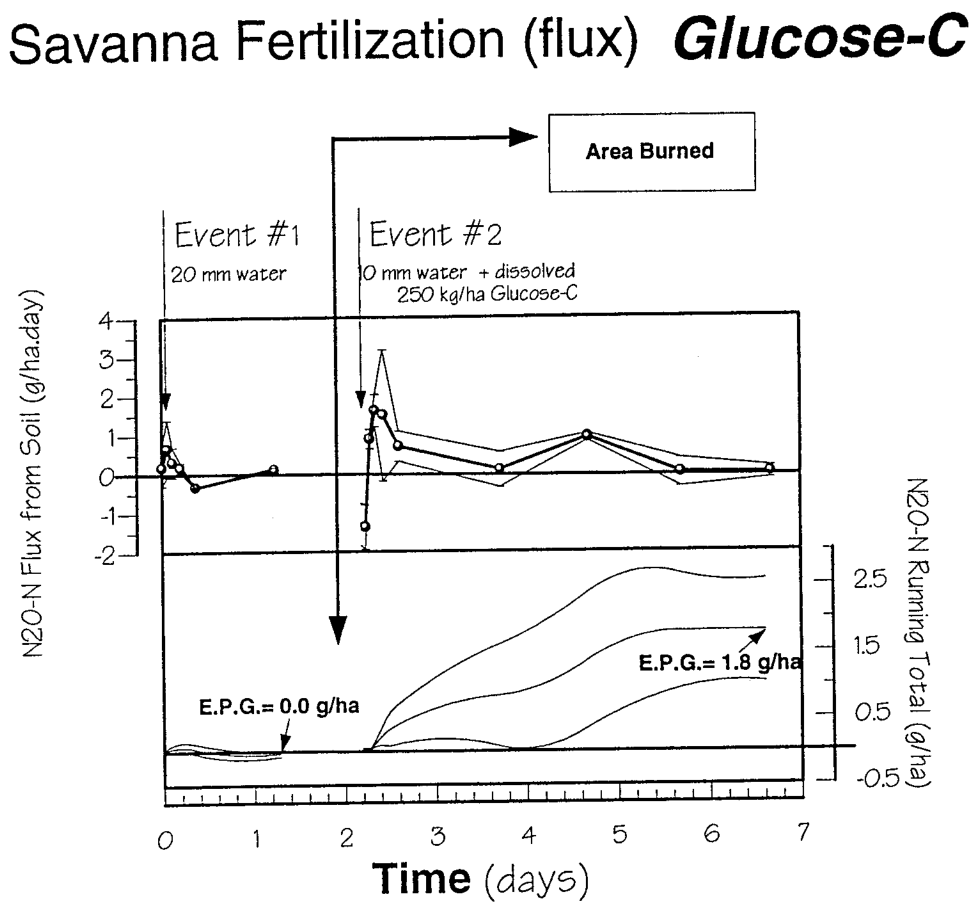

Figure II.5.C. FertEx N_2O emissions for Glucose-C treatment. Other features are the same as for Figure II.5.A.

Savanna Fertilization (flux) ***Nitrate-N + Glucose-C***

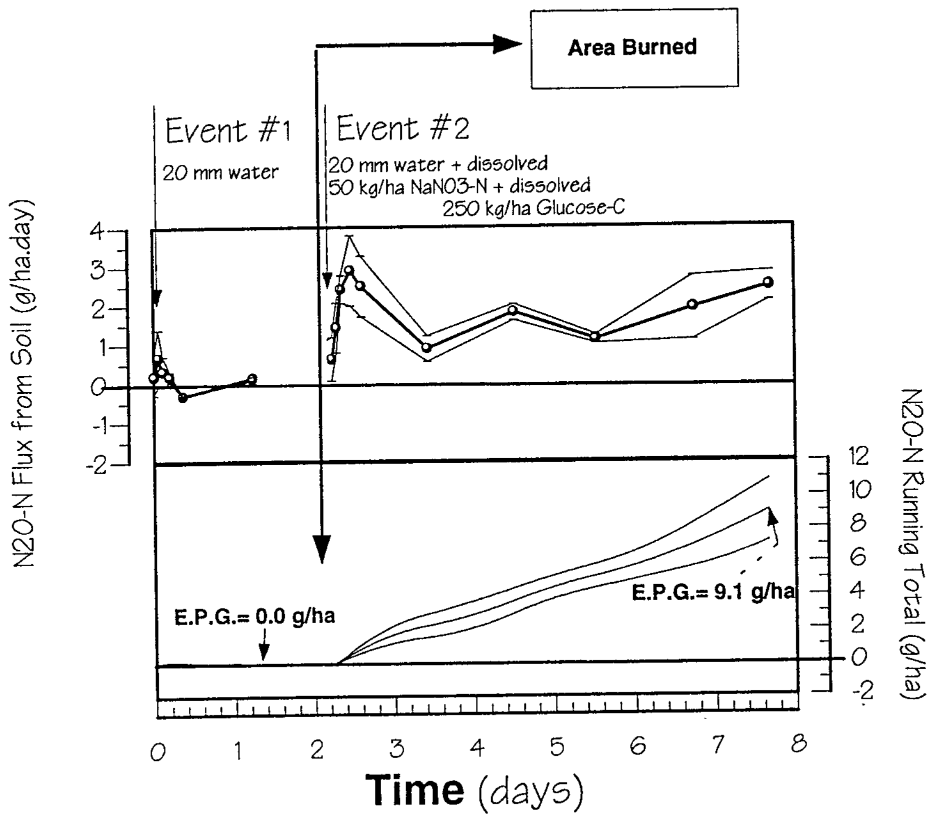

Figure II.5.D. FertEx N_2O emissions for Nitrate-N + Glucose-C treatment. Other features are the same as for Figure II.5.A.

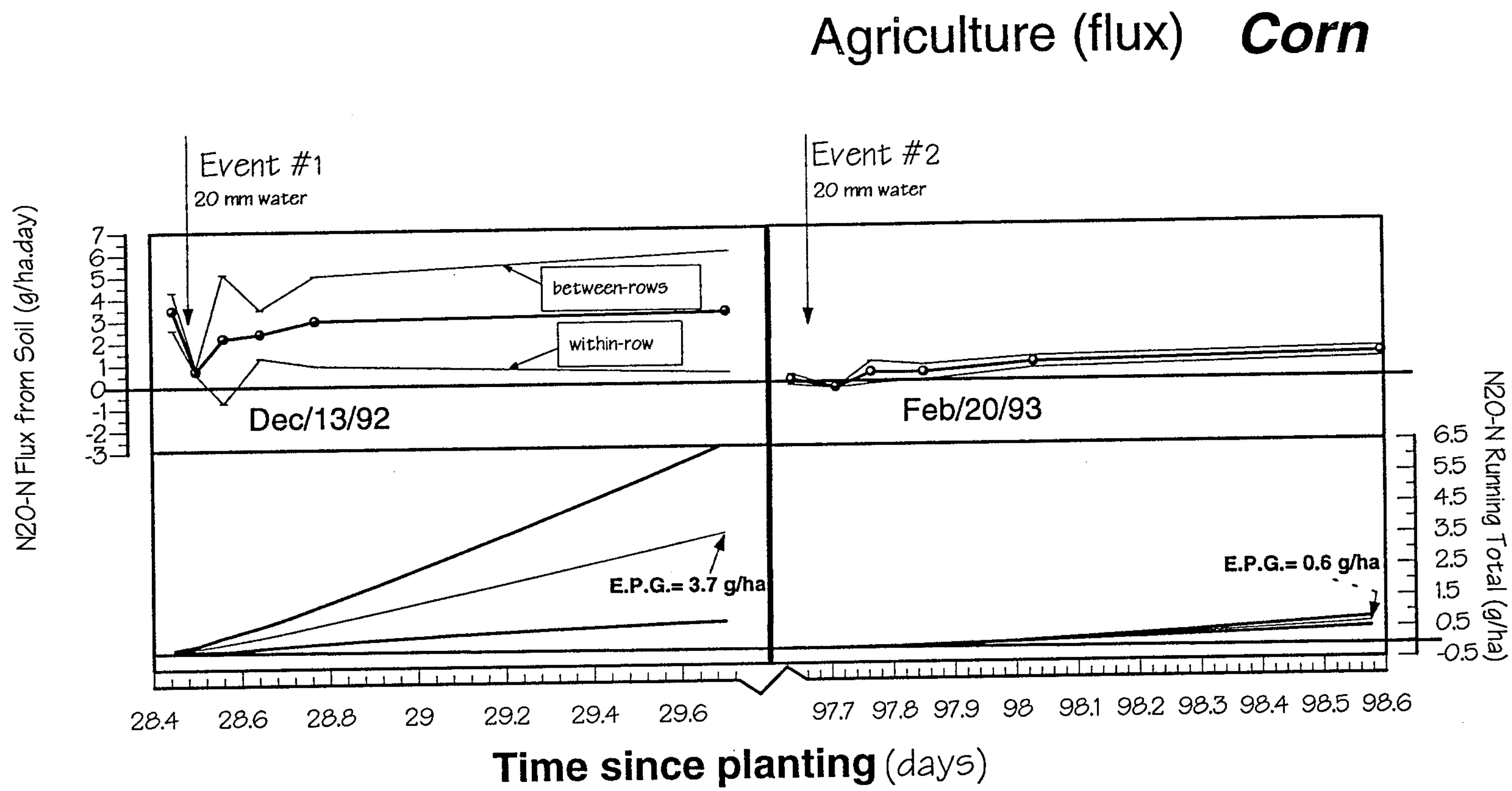

Figure II.6.A. APEx N_2O emissions for Corn (*Zea mayz*) plantation. The cumulative curves, or running totals, are integrated summations of interpolated intervals of the minimum sampling period (30 min.) for the entire event period. E.P.G. means event produced gas. Other features of the flux plots are the same as for Figure II.4.A.

Agriculture (flux) ***Soybean***

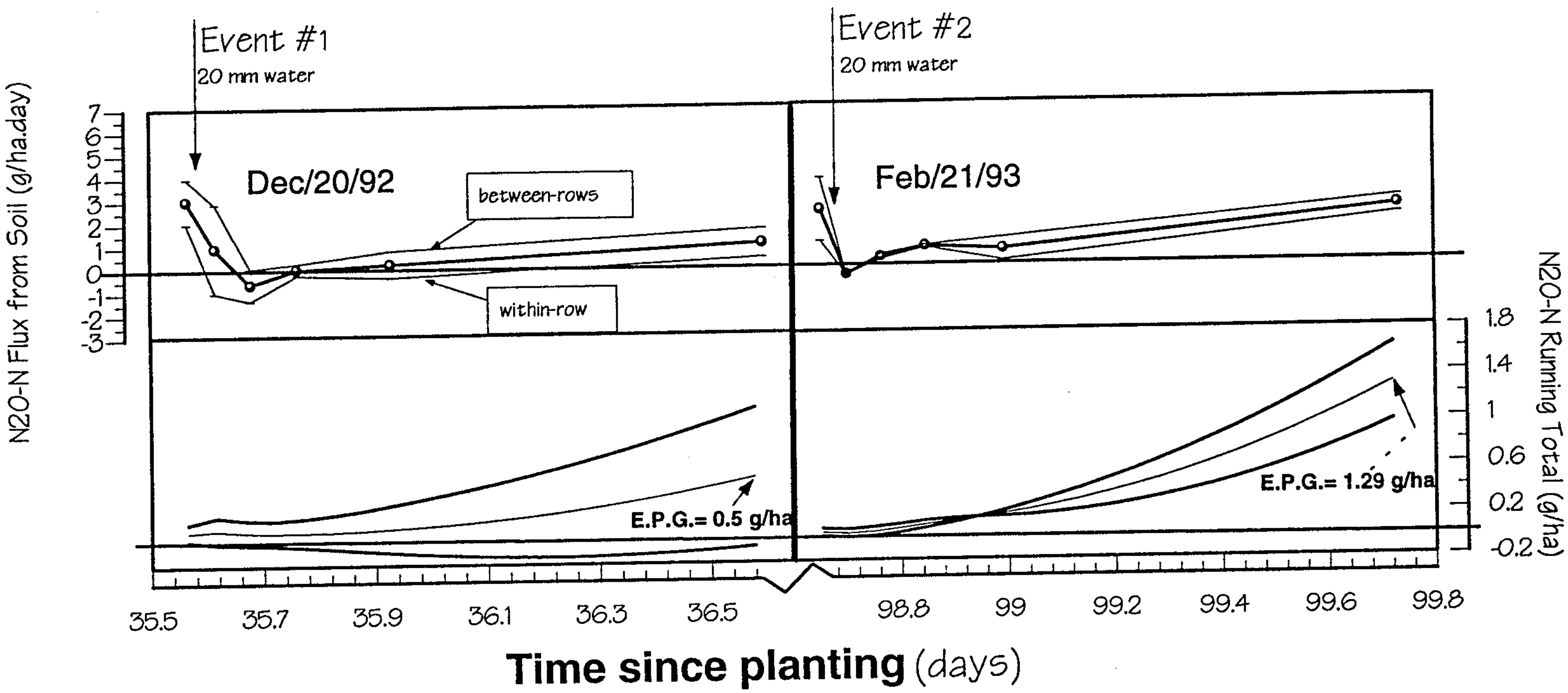

Figure II.6.B. APEx N_2O emissions for Soybean (*Glycinea max*) plantation. Other features are the same as for Figure II.6.A.

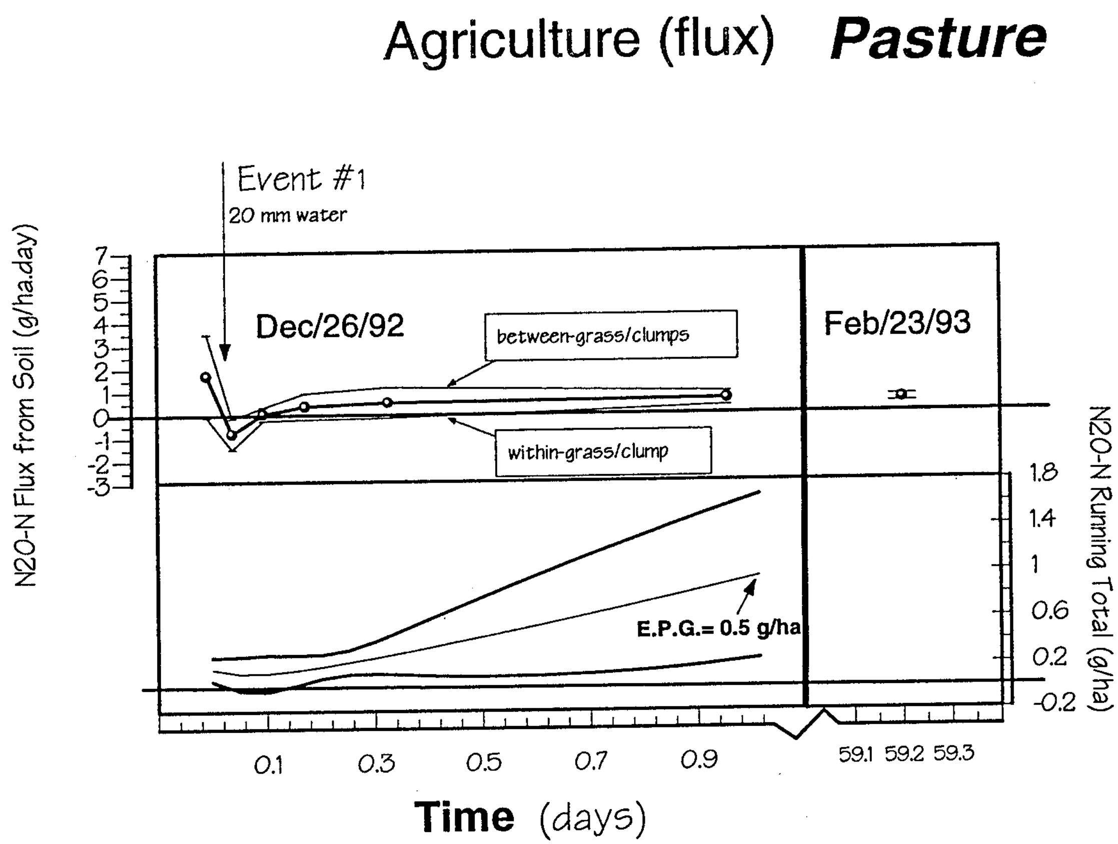

Figure II.6.C. APEx N_2O emissions for Pasture (*Paspalum* grass). Other features are the same as for Figure II.6.A.