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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-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$_2$O-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$_2$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.

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 km² (*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$_2$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

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 N₂O 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 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, α-D(+) $C_6H_{12}O_6$) 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 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$_2$O 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

$N_2O-N \cdot ha^{-1} \cdot d^{-1}$.

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 $N_2O\text{-}N \cdot ha^{-1} \cdot d^{-1}$ 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.

Tree/shrub savanna (Cs) . 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$_2$O-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$_2$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 · 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$_2$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 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$_2$O-N $\cdot$ 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$_2$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$_2$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$_2$O mixing ratios. Nevertheless, for both events and for almost all time-steps, there was a weak upward gradient in soil-gas N$_2$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$_2$O emission (Figure II.3.C; Table II.6).

The savanna woodland showed that despite weak upward soil N$_2$O gradients, and a detectable pulse in soil N$_2$O mixing ratios, fluxes at

the soil surface were less than 0.3 g N_2O-N $\cdot$ ha^{-1} $\cdot$ 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 $\cdot$ ha^{-1} $\cdot$ 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 $\cdot$ ha^{-1} $\cdot$ d^{-1} with an area-average of 0.6 g N_2O-N $\cdot$

ha^{-1} $\cdot$ d^{-1}. *Mosier* et al. (1991) studying two native grasslands in North

America found fluxes of 1.8 and 3 g N_2O-N $\cdot$ ha^{-1} $\cdot$ 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$_2$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.

<u>**Control Treatment**</u> . 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 $N_2O\text{-}N \cdot ha^{-1}$ in 96 h

$(0.45$ g $N_2O\text{-}N \cdot ha^{-1} \cdot d^{-1})$ (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 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$_2$O 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$_2$O-N $\cdot$ ha^{-1} in 96 h (1.1 g N$_2$O-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$_2$O-N $\cdot$ ha^{-1} in 96 h (0.45 g N$_2$O-N $\cdot$ ha^{-1} $\cdot$ 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$_2$O 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 $\cdot$ ha^{-1} in 96 h (2.3 g N$_2$O-N $\cdot$ ha^{-1} $\cdot$ 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)

<u>Corn (*Zea mayz*)</u> . 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 3.7 g N$_2$O-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$_2$O-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$_2$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 N$_2$O-N · ha^{-1} · d^{-1}, and averaged of 12 g N$_2$O-N

· ha^{-1} · d^{-1}. *Mosier* and *Hutchinson*, (1981) studying N$_2$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 N$_2$O-N · ha^{-1} ·

d^{-1}. They also found that approximately 30 % of the N$_2$O 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.

<u>Soybean (*Glycinea max*)</u> . 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 $\cdot$ 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$_2$O emission, instead of enhancing it as in systems where denitrification is strong, suggests that nitrification is the main pathway for N$_2$O production in this agroecosystem.

Annual average N$_2$O emissions measured by *Bremner* et al. (1980), from soybeans fields on six different temperate soils, ranged from 0.9 to 5.4 g N$_2$O-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$_2$O emissions from fields of cultivated legumes to be 23 to 315 Gg N$_2$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.

<u>Pasture</u> (*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$_2$O-N $\cdot$ 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$_2$O only in those areas fertilized directly by animal urine and feces.

The magnitude of N$_2$O 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$_2$O 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$_2$O production pathway.

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.

The cerrado biome as such, and during the wet season does not seem to be a major source of N$_2$O 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$_2$O emissions more than ten times.

Aknowledgment

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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 $N_2O\text{-}N \cdot ha^{-1} \cdot d^{-1}$

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

Table II.8. Mean N_2O Flux Measurements (in $g\ N \cdot ha^{-1} \cdot d^{-1}$) 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 $N_2O-N \cdot ha^{-1} \cdot d^{-1}$
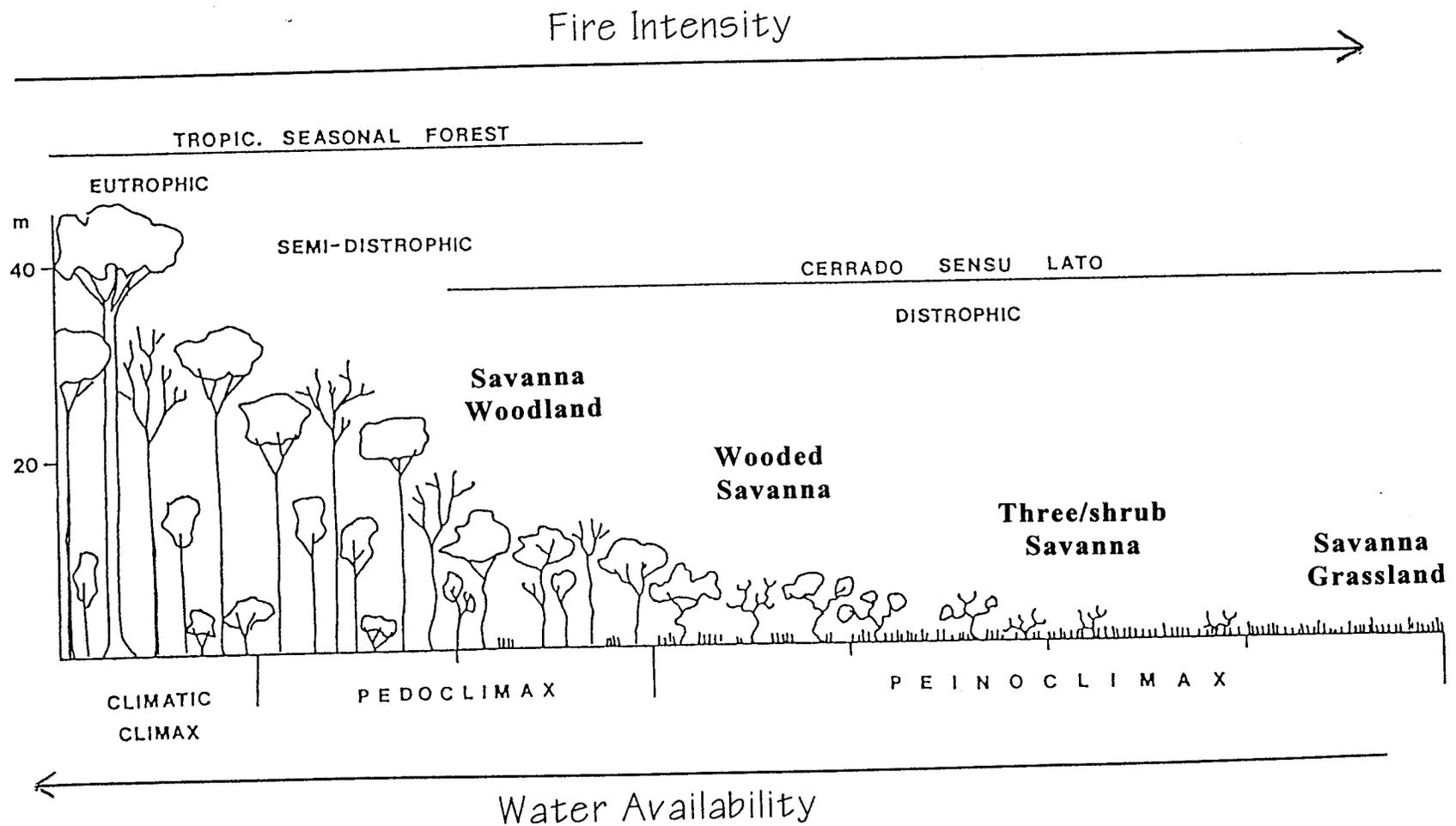
Figure II.1. The forest-savanna-grassland ecocline in central Brazil. Modified from *Countinho* (1990).

Savanna Grassland *Cl*

Area Burned in Sept 21/92

Event #2
20 mm water

N₂O-N Flux from Soil (g/ha.day)

4.75
3.5
2.25
1
-0.25
-1.5

0g N2O -N/ha.d

Soil Depth (cm)

2
5
10
20

N₂O in the Soil Gas-Phase (ppbv)

360 330 300 270 240 210 180
360 330 300 270 240 210 180
360 330 300 270 240 210 180
360 330 300 270 240 210 180

atm
atm
atm
atm

Nov 15/92
Feb/18/93

54 55   149 150 151 152 153 154

Time since fire (days)
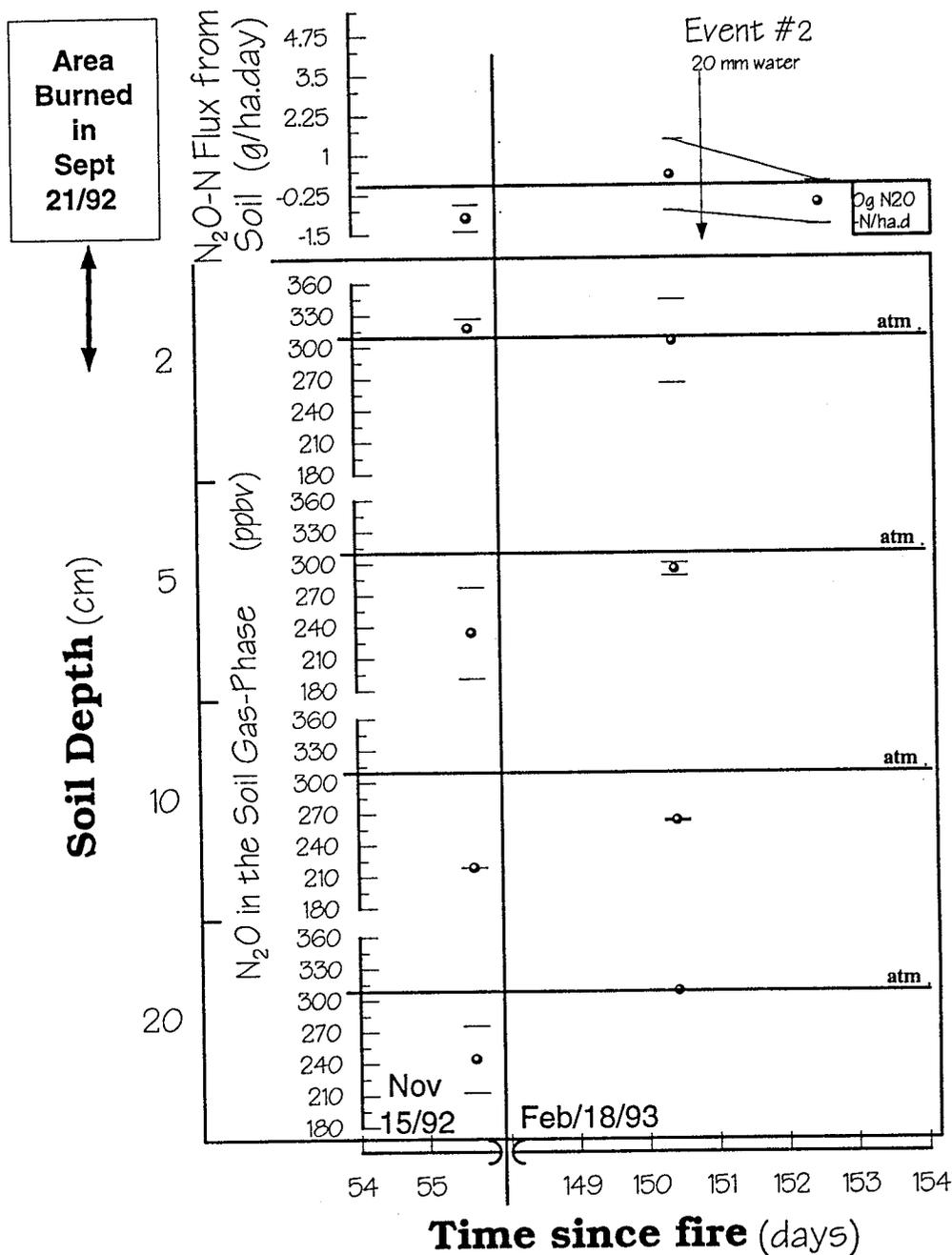
Figure II.2.A. FScars soil time-series data for savanna grassland (Cl) site. N₂O exchange flux with the atmosphere is shown on top of the soil profile, associated with soil gas-phase N₂O concentrations. An event refers to the addition of water to the experiment, and includes the subsequent drying period until the next event or until the end of the experiment. The atm. lines indicate ambient N₂O 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.
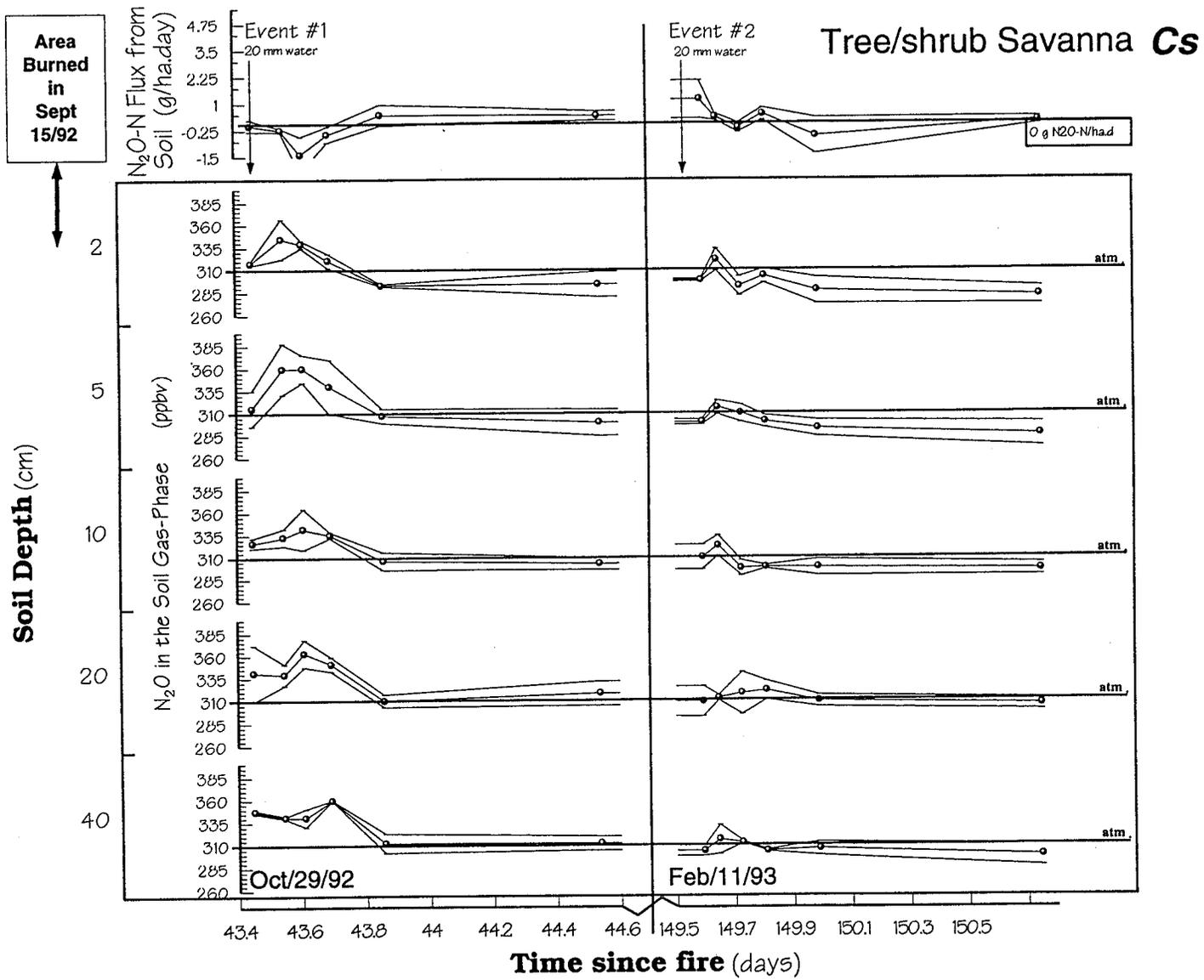
Figure II.2.B. FScars soil time-series data for tree/shrub savanna (Cs) site. Other features are the same as for Figure II.2.A.
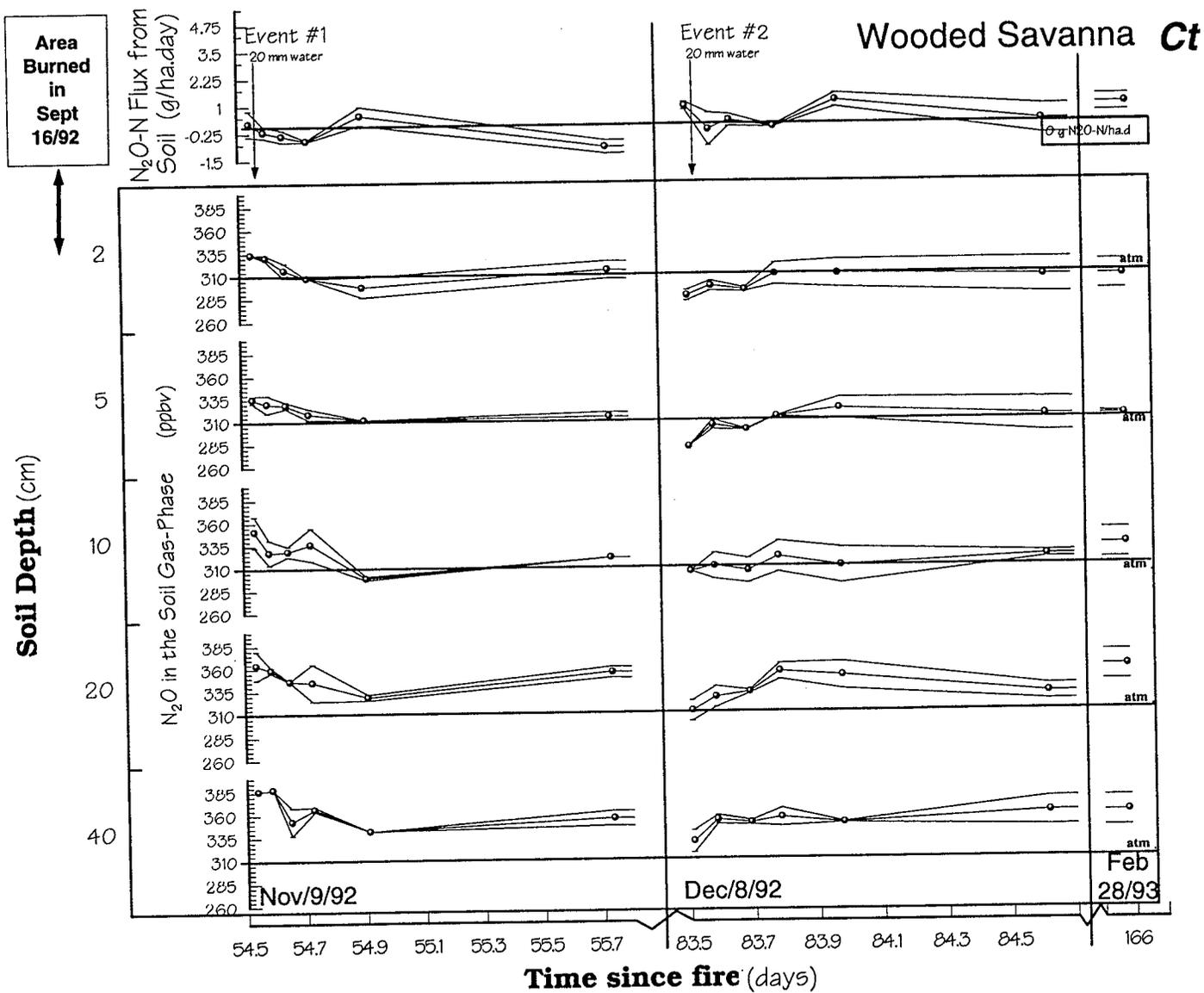
Figure II.2.C. FScars soil time-series data for wooded savanna (Ct) site. Other features are the same as for Figure II.2.A.
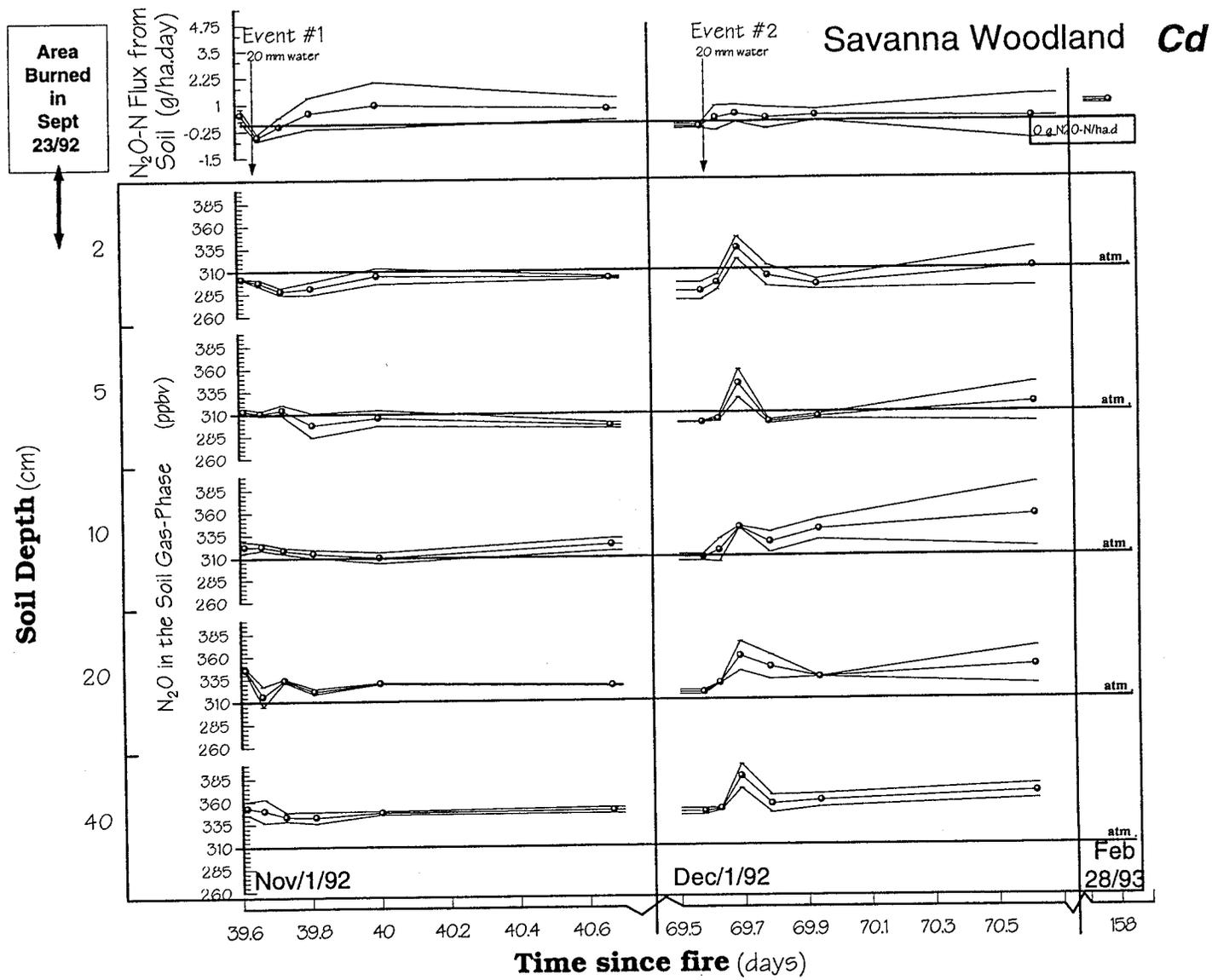
Figure II.2.D. FScars soil time-series data for savanna woodland (Cd) site. Other features are the same as for Figure II.2.A.

Area Burned in Sept 23/92

N_2O-N Flux from Soil (g/ha.day)

Event #1
20 mm water

Event #2
20 mm water

Savanna Woodland *Cd*

0 g N_2O-N/ha.d

Soil Depth (cm)

N_2O in the Soil Gas-Phase (ppbv)

atm.

Nov/1/92

Dec/1/92

Feb 28/93

Time since fire (days)

Tree/shrub Savanna (flux) **Cs**
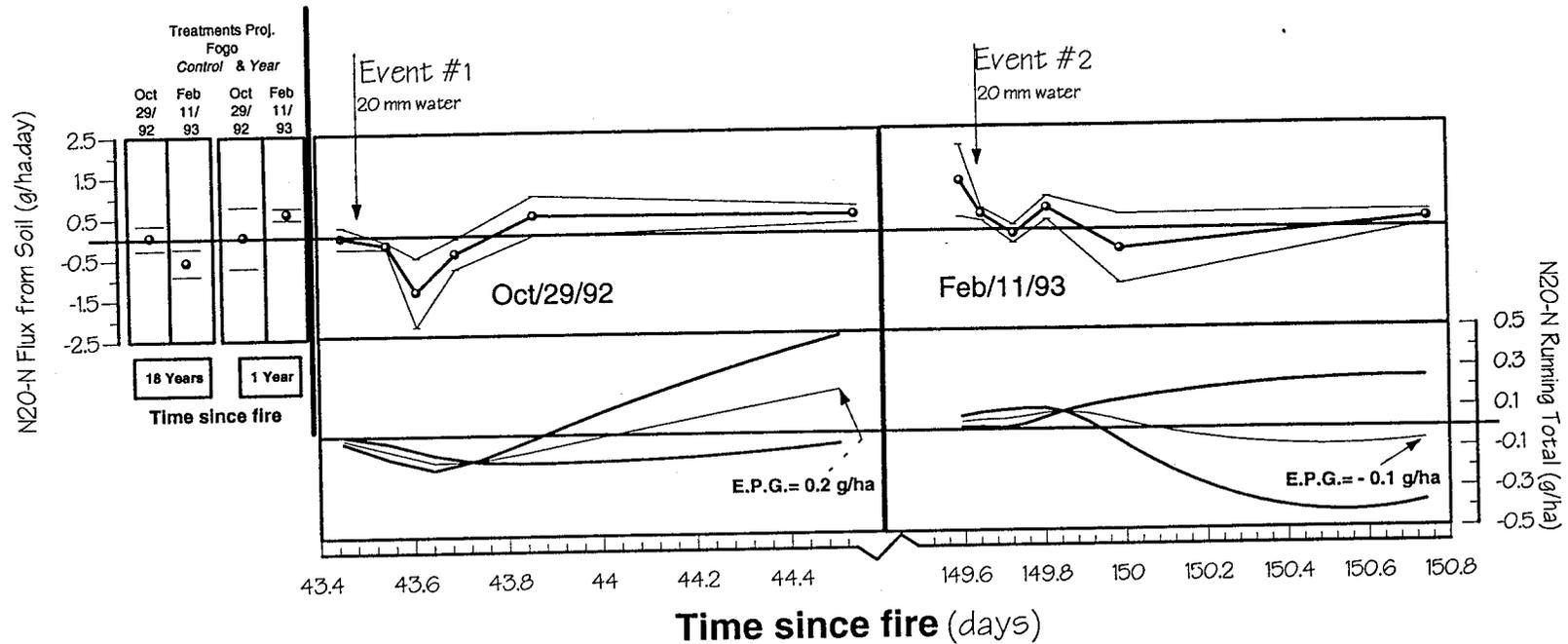
Figure II.3.A.   FScars N₂O emissions for tree/shrub savanna (Cs) site. The cumulative curves, or running totals, are integrated summations of interpolated intervals of the minimum sampling period (30 min.) for the entire event period. For a comparisson in this site, N₂O fluxes from a control plot not 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.

Wooded Savanna (flux) *Ct*
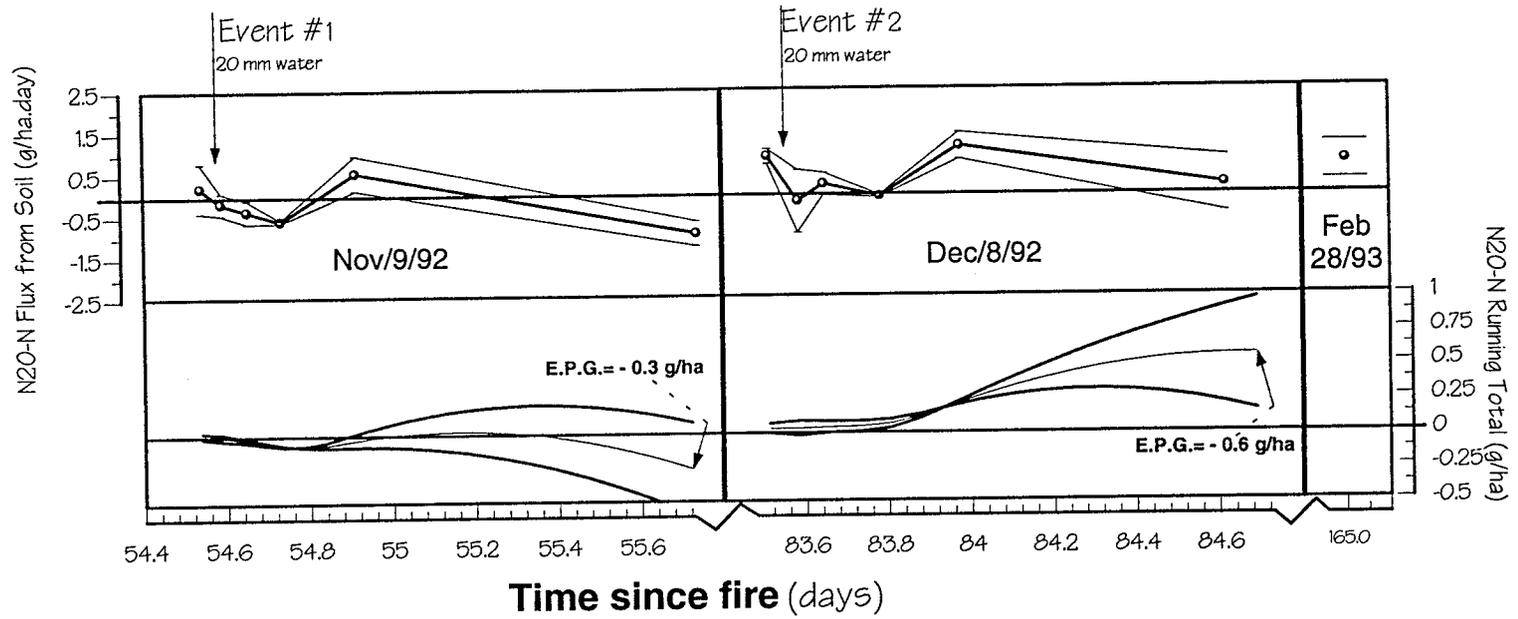
Figure II.3.B. FScars N$_2$O emissions for wooded savanna (Ct) site. Other features are the same as for Figure II.3.A.
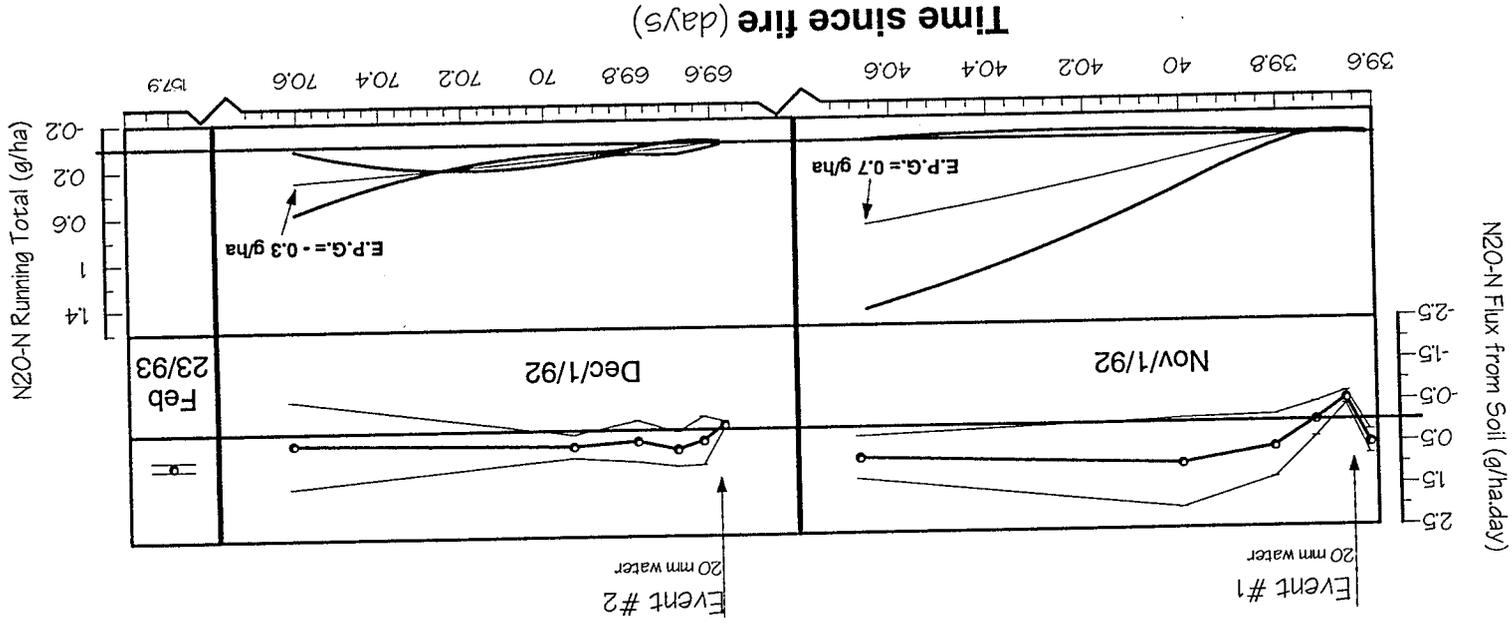
Figure II.3.C. FScars N₂O emissions for savanna woodland (Cd) site. Other features are the same as for Figure II.3.A.
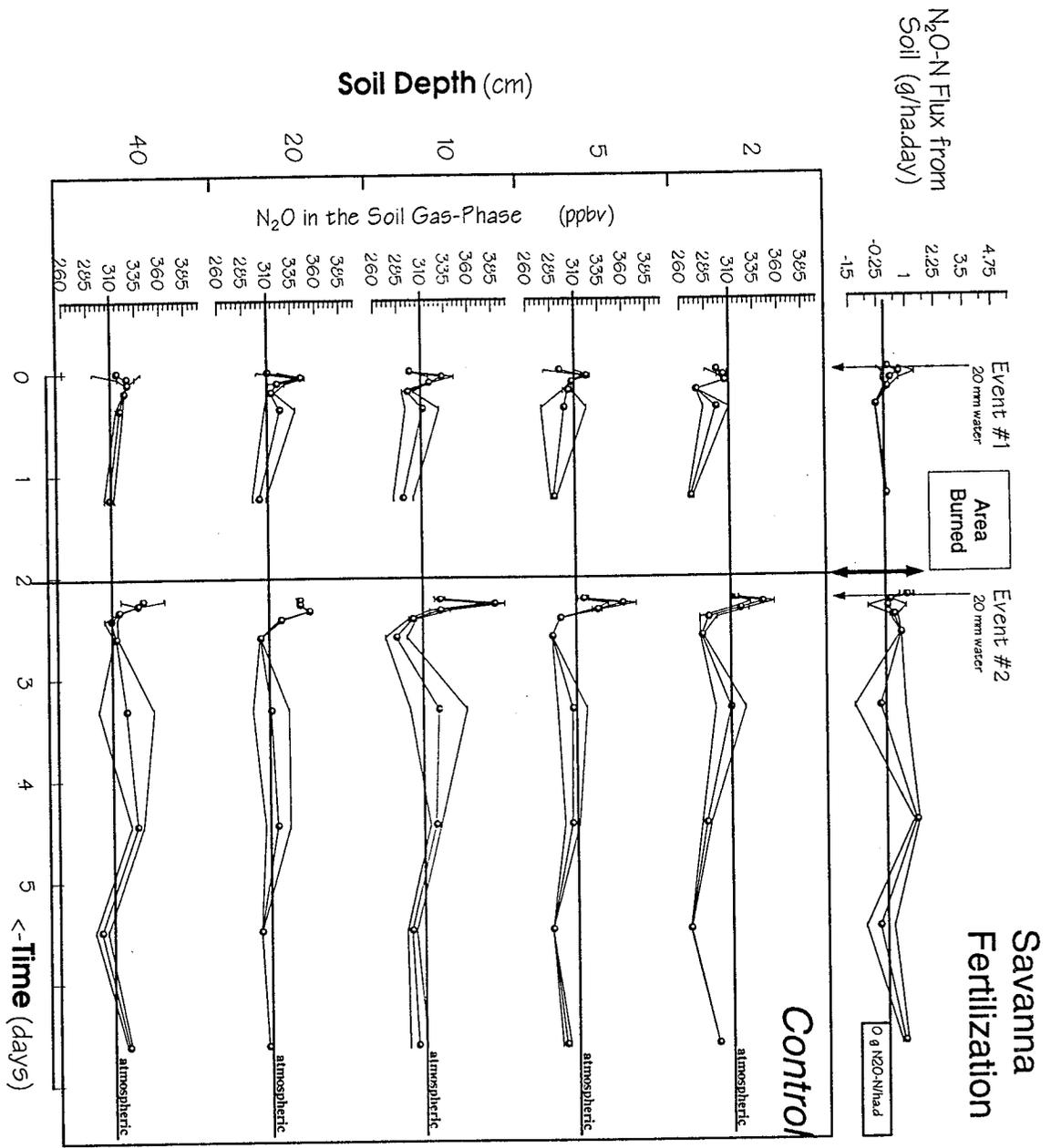
Figure II.4.A. FertEx soil time-series data for Control treatment. N_2O exchange flux with the atmosphere is shown on top of the soil profile, associated with soil gas-phase N_2O concentrations. An event refers to the addition of water to the experiment, and includes the subsequent drying period until 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.
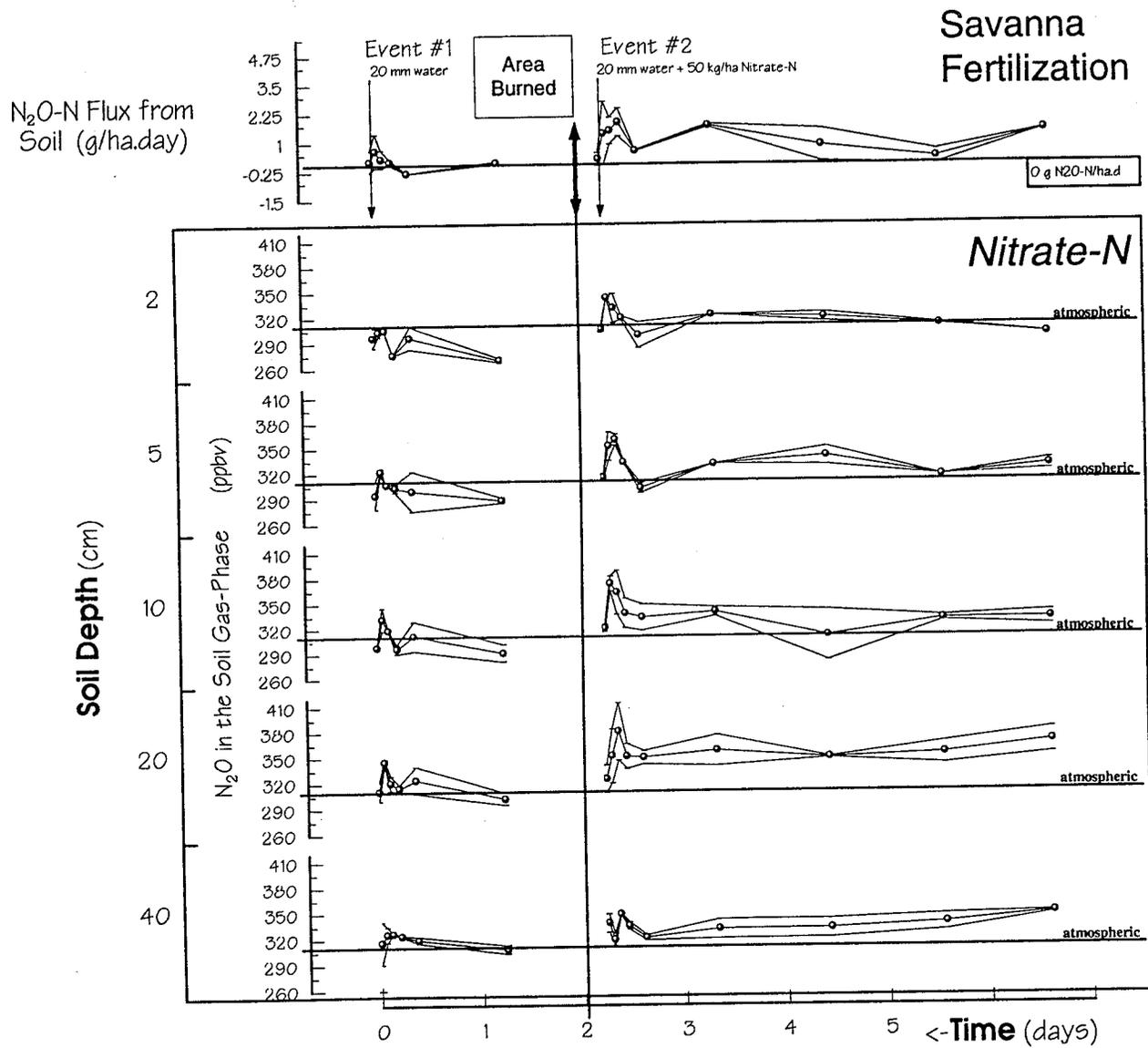
Figure II.4.B. FertEx soil time-series data for Nitrate-N treatment. Other features are the same as for Figure II.4.A.
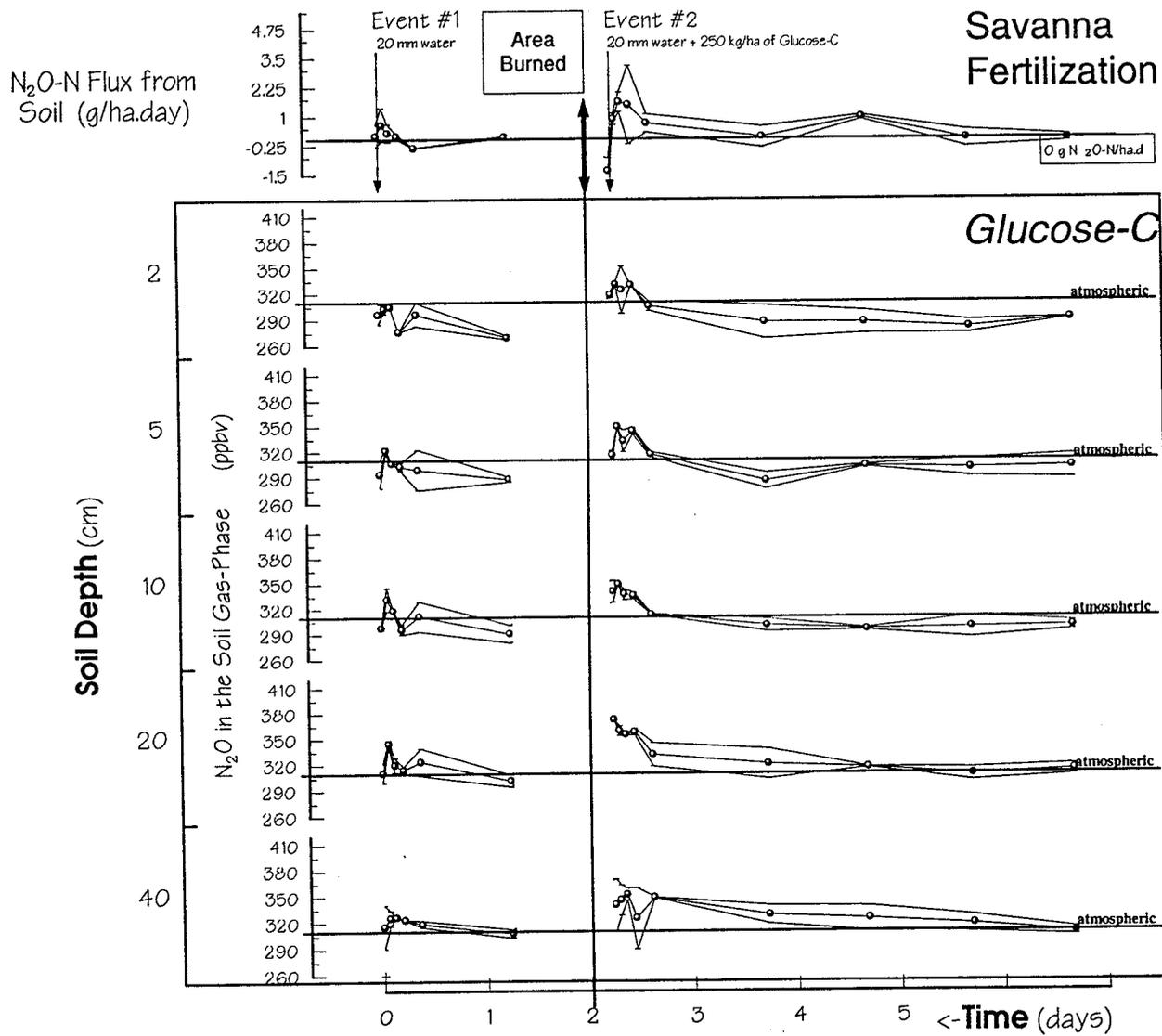
Figure II.4.C. FertEx soil time-series data for Glucose-C treatment. Other features are the same as for Figure II.4.A.
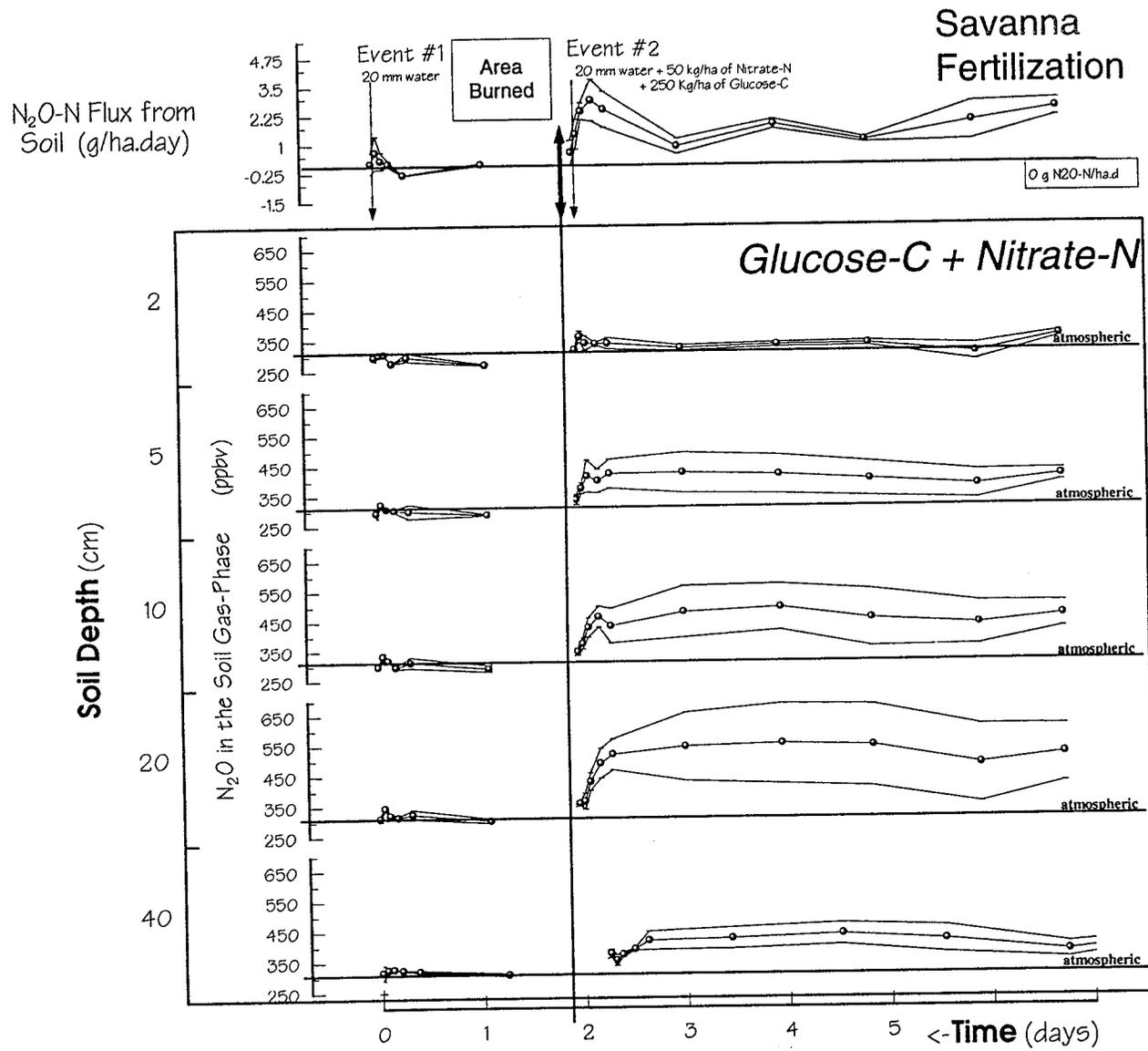
Figure II.4.D. FertEx soil time-series data for Nitrate-N + Glucose-C treatment. Other features are the same as for Figure II.4.A.

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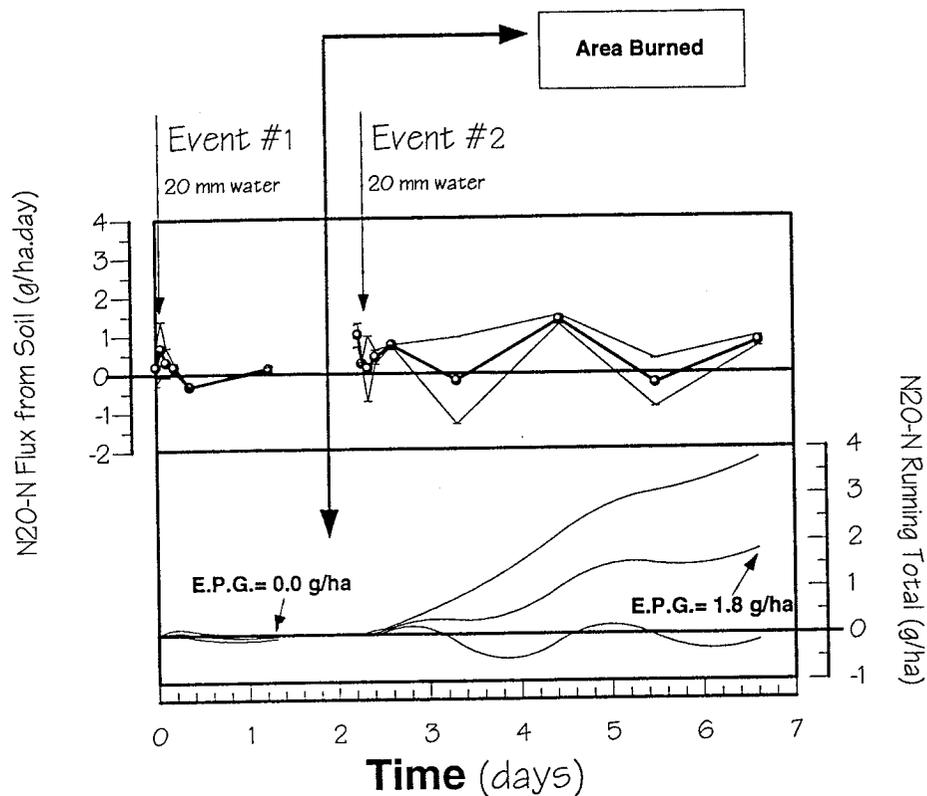
Figure II.5.A. FertEx N_2O emissions for Control treatment. The cumulative curves, or running totals, are integrated summations of interpolated intervals of the minimum sampling period (30 min.) for the entire event period. E.P.G. means event produced gas. Other features of the flux plots are the same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

Savanna Fertilization (flux)   *Nitrate-N*
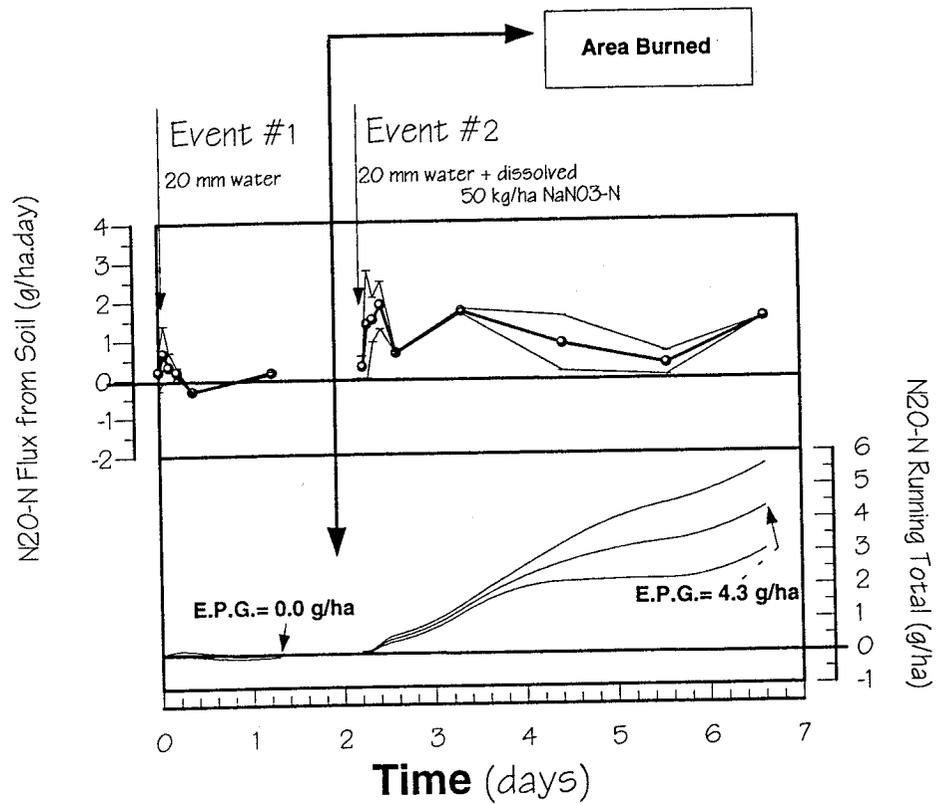
Figure II.5.B.   FertEx N$_2$O emissions for Nitrate-N treatment.   Other features are the same as for Figure II.5.A.

Savanna Fertilization (flux) *Glucose-C*
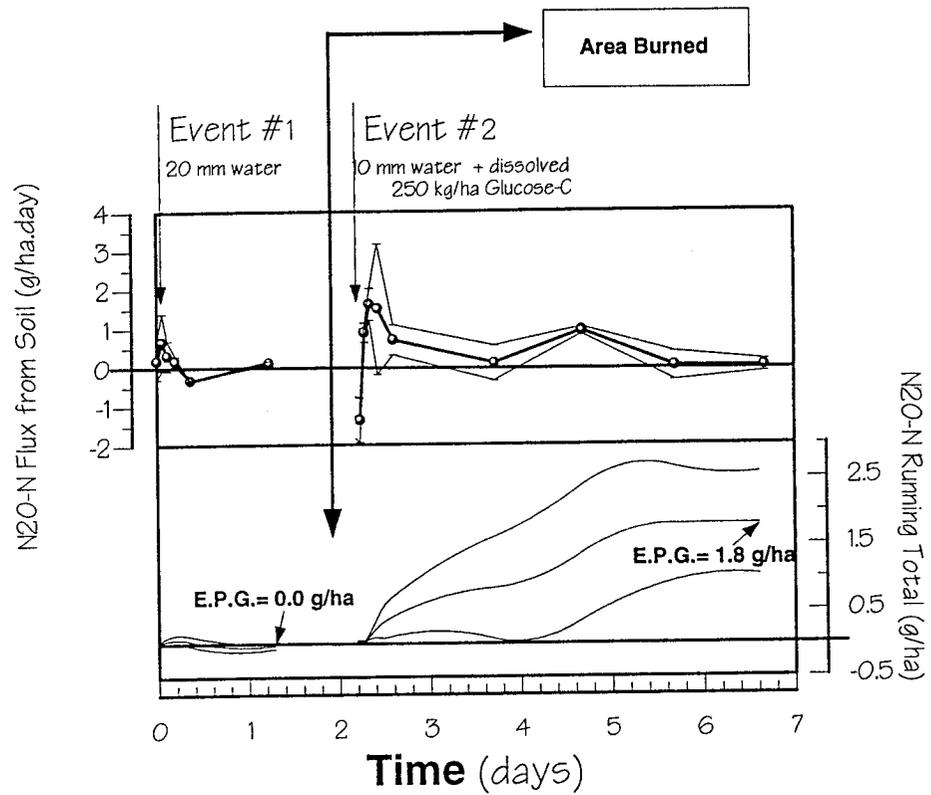
Figure II.5.C. FertEx N_2O emissions for Glucose-C treatment. Other features are the same as for Figure II.5.A.

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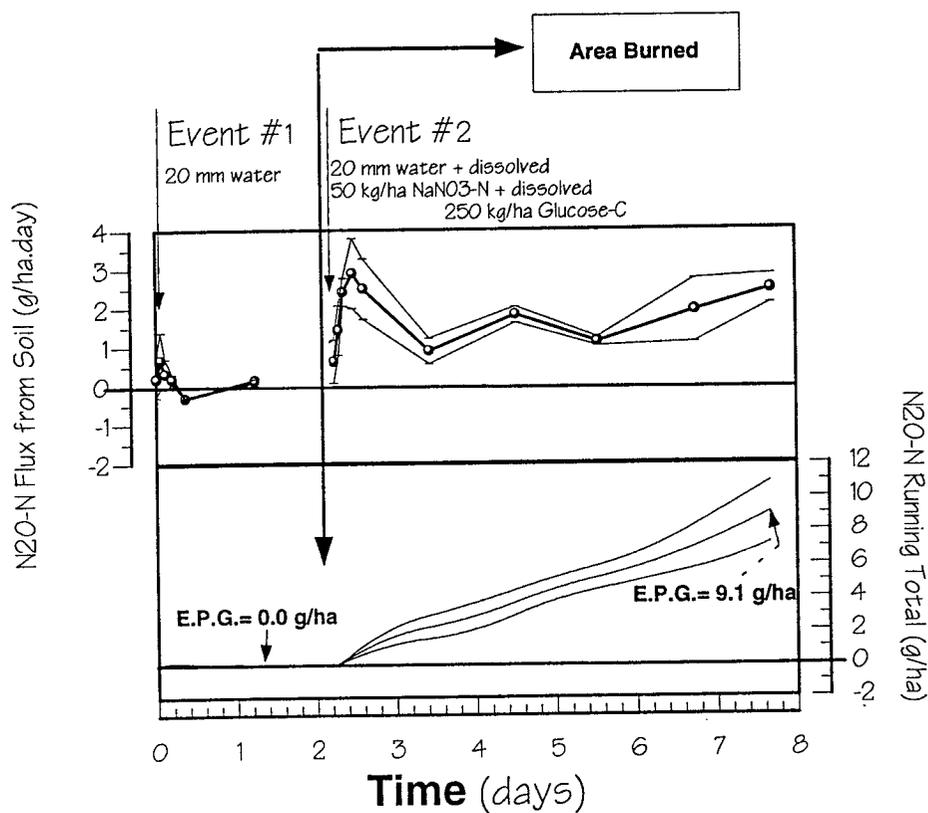
Figure II.5.D. FertEx N$_2$O emissions for Nitrate-N + Glucose-C treatment. Other features are the same as for Figure II.5.A.

Agriculture (flux) *Corn*
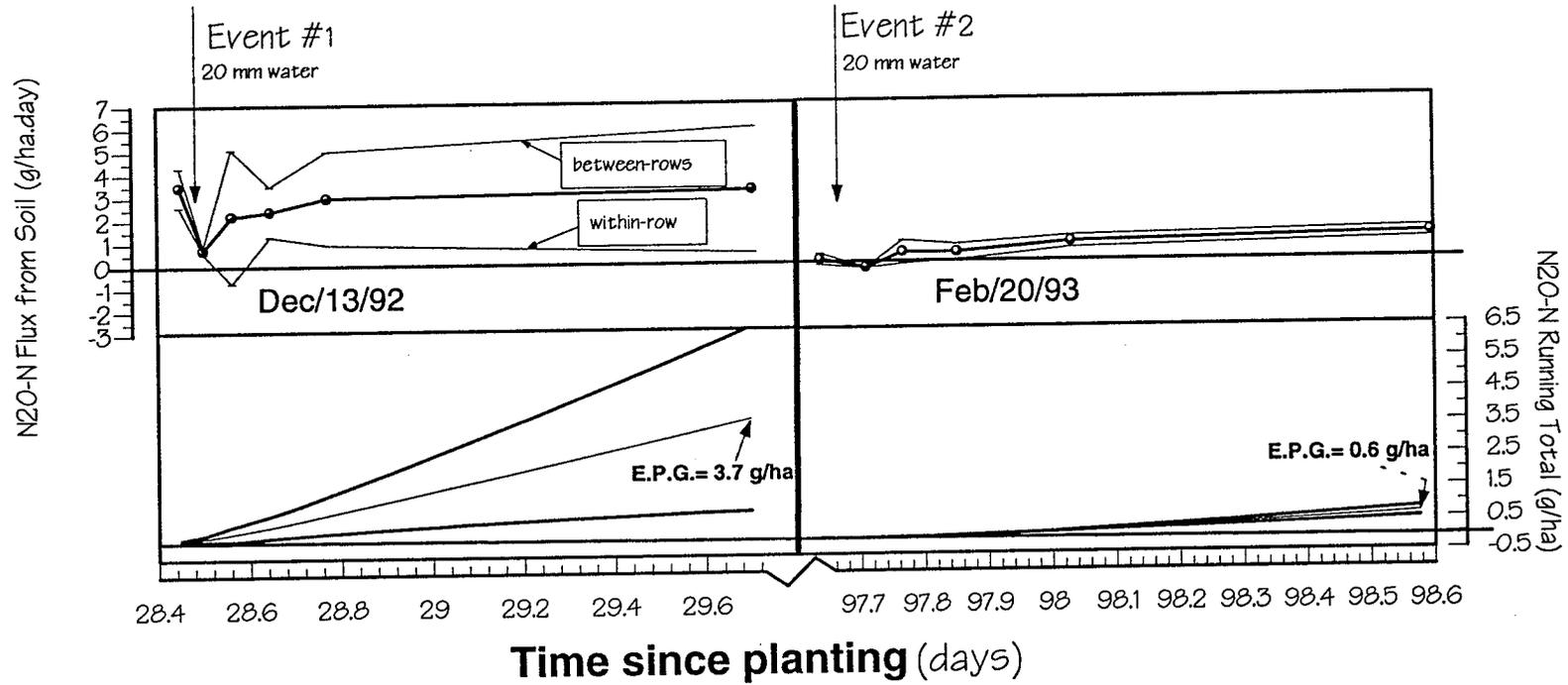
Figure II.6.A. APEx N$_2$O emissions for Corn (*Zea mayz*) plantation. The cumulative curves, or running totals, are integrated summations of interpolated intervals of the minimum sampling period (30 min.) for the entire event period. E.P.G. means event produced gas. Other features of the flux plots are the same as for Figure II.4.A.
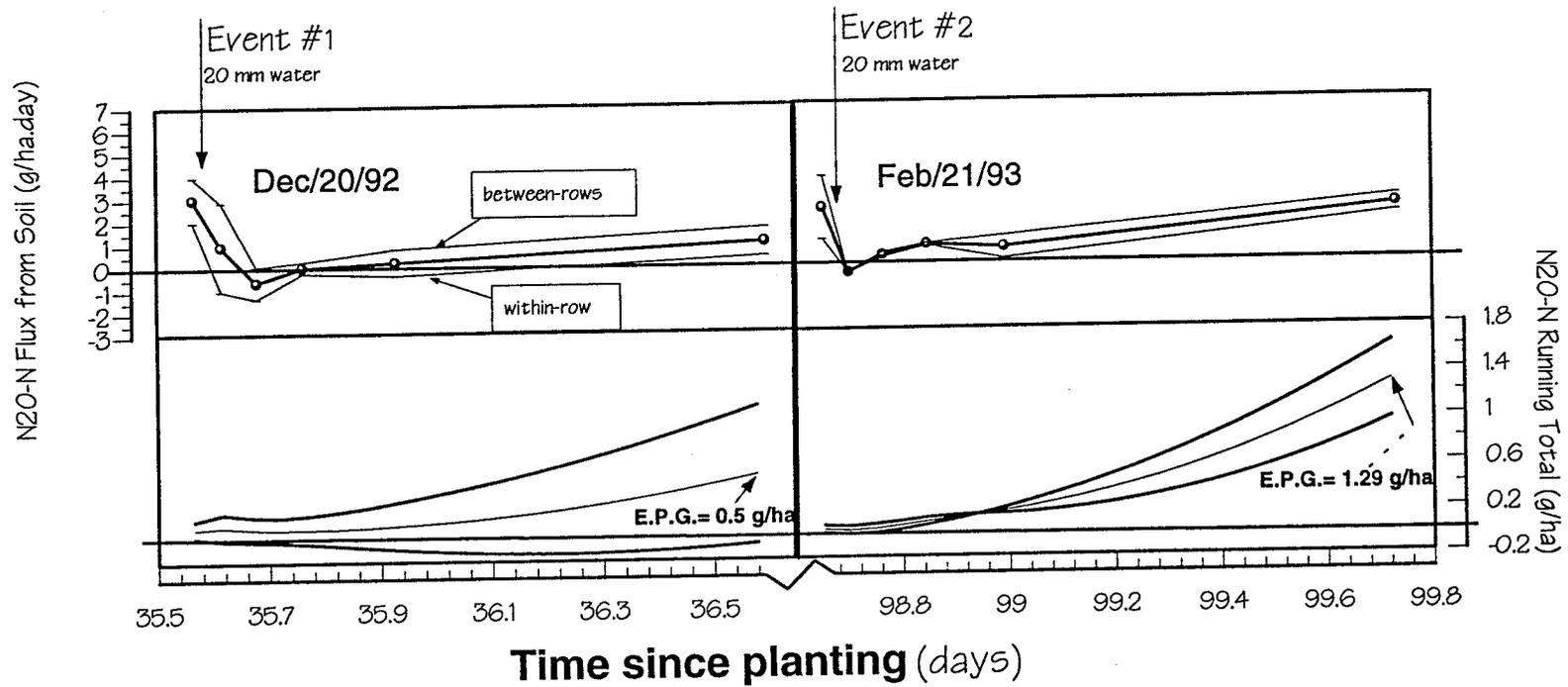
Figure II.6.B. APEx N₂O emissions for Soybean (*Glycinea max*) plantation. Other features are the same as for Figure II.6.A.

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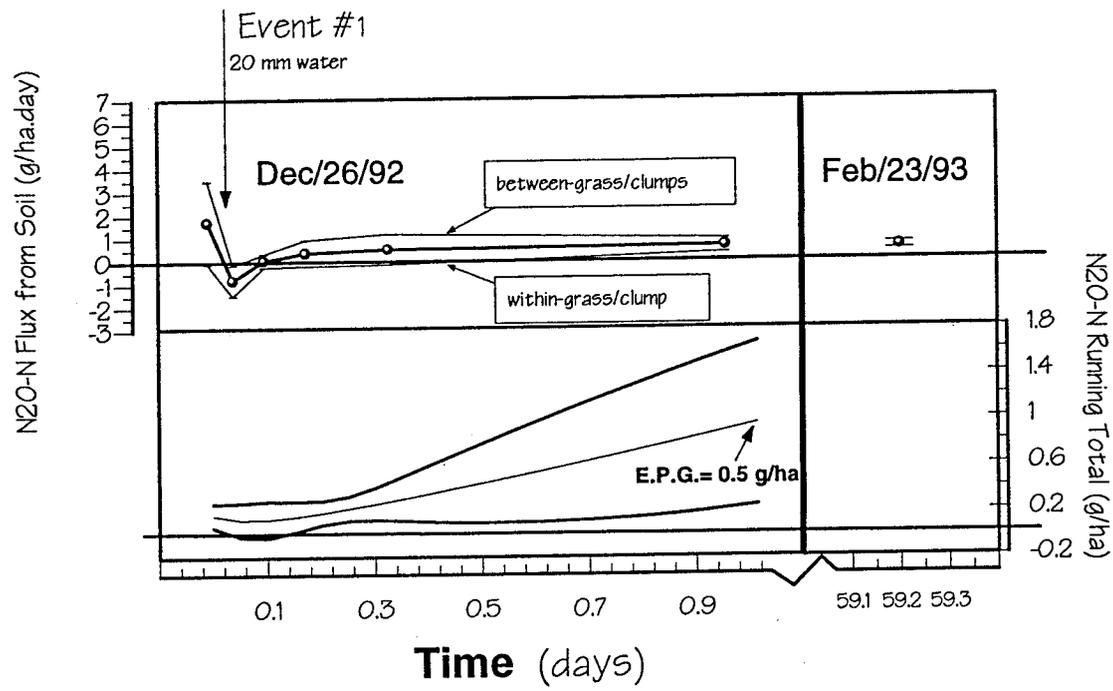
Figure II.6.C.   APEx N₂O emissions for Pasture (*Paspalum* grass). Other features are the same as for Figure II.6.A.