Fall 1994

Nitrous oxide emissions from tropical soils

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Nitrous oxide emissions from tropical soils

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University of New Hampshire, 1994

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NITROUS OXIDE EMISSIONS FROM TROPICAL SOILS

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DISSERTATION

Submitted to the University of New Hampshire
in Partial Fulfillment of
the Requirements for the Degree of

Doctor of Philosophy

in

Earth Sciences

September, 1994

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Date

This dissertation is dedicated

with love

to the elemental beings of

soil and air.

ACKNOWLEDGMENTS

For the second time in my graduate life, I am able to thank my advisor, mentor and friend, Bob Harriss, for his support, tolerance, kindness, wisdom, and farsighted enthusiasm. For the longer haul, I thank my parents, Nair and Wilson, for bringing me to this wonderful planet and my brother Carlos for the early inspiration and support which lead me into science. I am indebted to Patrik Wiedemeir and Reto Stoker for giving me the opportunity to continue my crusade against the destruction of the tropical rainforest. Katherine Bolster through her delicate grace, emotional support and competent advice on programming and editing help carry me through to the completion of this dissertation.

The Complex Systems Research Center staff, namely Karen Bushold, Linda Tibbetts and Diana Wright offered the kind of encouragement and support that helped to make me have the most productive professional four years of my present life. I thank Patrick Crill and Michael Keller for introducing me and getting me to appreciate the technical side of trace-gases. I thank also Steve Frolking, Changsheng Li and John Aber for introducing me and getting me to appreciate the modeling side of trace gases and Mark Hines for acquainting me with an exciting biogeochemical way to see the world. In Costa Rica I am thankful to Rodolfo Vargas, Danilo Villegas, and Marvin Nunez for their assistance in the field and lab, and to the National Science Foundation Huerto's

iv

Copies of this work should mention its true inspirational source:
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v

PREFACE

This dissertation consists of two parts, each one standing alone as a comprehensive approach to its respective subject. However, when taken together these two studies encompass an interesting spectrum of possibilities for helping to solve the puzzle of the missing nitrous oxide source in the global budget. The following is a brief summary of each part.

Part I - Short-Term Response Of Nitrous Oxide Emissions To Nitrogen And Carbon Additions In Two Tropical Volcanic Soils.

This part presents a detailed study of volcanic soils of high natural fertility, located at La Selva Biological Station in Costa Rica. Originally the area had a lush tropical rainforest cover, which since has been converted to agricultural use. The experiments described in this part stress two key approaches to nitrous oxide production, namely rainfall-driven episodic short-pulses of emissions, and emission-response to different kinds of fertilizers. The monitoring of soil-profile inorganic-nitrogen chemistry and soil-moisture, simultaneously with nitrous oxide production and emission over time, is, to date, unique to this study.

Part II - **Episodic Nitrous Oxide Soil Emissions In Brazilian Savanna (Cerrado) Fire-Scars.**

The second part reports on a study of savanna ecosystems in tropical South America and their conversion to high input agriculture. The natural savanna, locally called cerrado, occurs on a highly infertile soil, as opposed to the soils in Costa Rica, which suffers periodic fires leaving behind large expanses of fire-scarred savanna. Nitrous oxide emissions for these impacted savannas previously were unknown. The first segment of this study, covering most of one rainy season, assesses several fire-scars from prescribed fires. The second segment of this study describes a series of fertilizations and subsequent episodic emissions carried out on a recently burned patch of natural savanna. This experiment was similar to the addition experiments in Costa Rica, so results could be compared and contrasted. And finally, the third segment of this study consists of monitoring episodic nitrous oxide emissions from pasture, and corn and soybean plantations, the three most common agricultural uses of the savannas.

vii

TABLE OF CONTENTS

viii

LIST OF TABLES

x

LIST OF FIGURES

xi

xii

ABSTRACT

NITROUS OXIDE EMISSIONS FROM TROPICAL SOILS

by

Antonio Donato Nobre
University of New Hampshire, September 1994

Nitrous oxide (N_2O), the third most important greenhouse trace gas in the troposphere and one contributor to ozone destruction in the stratosphere, has its concentration in the atmosphere increasing steadily over the last few decades. This study measured sources from tropical soils, potentially the highest and least studied N_2O production areas in the world.

For two tropical volcanic soils in Costa Rica the effect of water, nitrate and glucose additions on episodic emissions of nitrous oxide were studied. Magnitudes of episodic N_2O pulses, as well as overall N_2O emissions, varied considerably and consistently, depending on soil texture, soil moisture, and kind and availability of substrates. Emission pulses began within 30 minutes, peaking no later than 8 hours after wetting. Production in the soil occurred mainly in the layer between 5 and 20 cm deep, but depended directly on the temporal dynamics of the water profile. Soil inorganic nitrogen was associated with soil N_2O concentration changes. Depending on the treatment, one episodic N_2O production event driven by one moderate rain could account for less than 15% to more than 90 % of the total weekly production. Previous survey studies may have underestimated the contribution of gas emissions from tropical soils to

the global budget of N_2O, and better budgets will demand a detailed knowledge of both background emissions, and episodic emissions driven by rain events.

The seasonally burned cerrados of Brazil are the largest savanna-type ecosystem of South America and their contribution to the global atmospheric N_2O budget is unknown. Results showed that N_2O consumption/emission for four fire-scarred savanna ecosystems, for nitrogen and carbon fertilization and for agriculture/pasture ranged from -0.3 to +0.7, 1.8 to 9.1, and 0.5 to 3.7 g N_2O-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, conversion of the cerrado to high input agriculture, with liming and fertilization, can increase N_2O emissions more than ten fold.

PART I

SHORT-TERM RESPONSE OF NITROUS OXIDE EMISSIONS TO NITROGEN AND CARBON ADDITIONS IN TWO TROPICAL VOLCANIC SOILS

Introduction

Before the industrial age, the atmospheric nitrous oxide concentration (mixing ratio) appears to have remained constant at around 285 ± 1 parts per billion by volume (ppbv) for the past 3000 years (*Khalil* and *Rasmussen*, 1988). However, over the past century the mixing ratio has increased about 8%, and during the past decade it has shown a yearly increase from 0.2% to 0.3% (*Khalil* and *Rasmussen*, 1983; *Khalil* and *Rasmussen*, 1992; *Prinn* et al., 1990; *Weiss*, 1981). There is a very high likelihood that the increase in N_2O atmospheric mixing ratio is directly associated with large scale human interference in the nitrogen cycle (*IPCC*, 1990). The current measured mixing ratio of N_2O in the troposphere is about 310 ppbv (*IPCC*, 1990). Nitrous oxide is an important greenhouse gas and is a factor in determining the ozone concentration in the stratosphere (*Cicerone*, 1987; *Dickinson* and

2

Cicerone, 1986; *Hahn* and *Crutzen*, 1982; *Singh*, 1987). The current sources of N_2O are poorly known, and inputs to the atmosphere, known and estimated, account for3 only about half of the flux required to balance the relatively well known destruction rate (*Kim* and *Craig*, 1993; *Robertson*, 1993).

Of the presently known sources, soils are estimated to be the largest, contributing approximately 66% of total emissions (*Robertson*, 1993 and references therein; *Davidson*, 1991 and references therein); 50% of the soil emissions are currently thought to be from undisturbed ecosystems. Comparative measurements have reported higher rates of denitrification and nitrous oxide release in tropical than in temperate forests (e.g. *Robertson* and *Tiedje*, 1986; *Seiler* and *Conrad*, 1987), sometimes by a factor of 20 larger than the global mean of nitrous oxide emissions by soils (*Keller* et al., 1983). Denitrification in tropical soils may account for up to half of the global production of N_2O (*Griffiths* et al., 1993). The Amazon basin, for instance, appears to be a major source of trace gases, including N_2O (*Matson* et al., 1987). Tropical biomes cycle larger amounts of total nitrogen than boreal ecosystems (*Chapin* et al., 1986; *Matson* and *Vitousek*, 1987; *Vitousek* and *Matson*, 1988; *Vitousek* and *Matson*, 1993; *Vitousek* and *Sanford*, 1986). Tropospheric N_2O mixing ratios over that basin are higher than the global average

3

(*McElroy* and *Wofsy*, 1986), although specific sources within the region have not yet been well quantified. To date, a disproportionate amount of information has come from the developed temperate regions of the northern hemisphere (*Smith* and *Arah*, 1990; *Vitousek* and *Matson*, 1993).

Nitrous oxide production and consumption in soil have been demonstrated to be a non-continuous process in both time and space (e.g. *Terry* et al., 1981). Its episodic nature, with pulses of production associated with major transient changes in soil microsite environments, has been shown to account for significant surges of emissions to the atmosphere in relatively short spans of 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).

Most previous survey studies carried out for tropical soils have not used high frequency (e.g. every few hours) sampling based on rain events to guide sampling. More commonly, daily sampling is conducted for only a short campaign (e.g. *Livingston* et al., 1988; *Goreau* and *Mello*, 1987; *Keller*, et al., 1983; *Matson* et al., 1990), or a few complete seasonal cycles are studied, sampling approximately every week (e.g. (*Keller* et al., 1993; *Luizão* et al., 1989).

4

Davidson et al. (1993) and *Garcia-Mendez* et al. (1991) studied a dry tropical forest and sampled rain-driven episodic events. They reported that the magnitude of the episodic events was a direct function of substrate accumulation during the dry season, and that the magnitude decreased with each successive rainfall until rain associated emissions were not distinguishable from the background. This finding might be a good approximation for most of the relatively arid and infertile nitrogen-limited natural ecosystems in the tropical and subtropical regions (see Part II). However, as these ecosystems are converted to agriculture, pasture or silviculture (*Fearnside*, 1986; *Skole* and *Tucker*, 1993), where some form of nitrogen fertilization is used (*Duxbury* et al., 1993; *Vitousek* and *Matson*, 1993), there is an increasing potential for episodic emissions to become significant.

In this paper, we report on a detailed study carried out on two tropical soils, converted previously from rainforest cover to agroforestry and pasture. The study was designed to respond to a recognized urgent need for field studies in which N_2O flux measurements are investigated in combination with processes regulating gas production and their environmental controls (*Schimel* et al., 1989). The study also was planned in conjunction with the development of a process oriented model,

5

DNDC (*Li* et al., 1992a) and (*Li* et al., 1992b), both efforts seeking to assess the unique role of rainfall events in soil denitrification.

Methods

Study Site

La Selva, a 3300 ha biological station of the Organization for Tropical Studies, lies between the confluence of the rivers Viejo and Sarapiqui, province of Heredia (10° 26' N; 83° 58' W, 40 m approx. elevation asl), in the transition zone from the coastal plain to the steep foothills of the Costa Rican Cordillera Central mountain range's north facing Caribbean slope. The terrain of the reserve is developed on andesitic lava flows deposited in the Pleistocene, and on alluvium, also derived from volcanic rock, overlying lava flows in terraces bordering both rivers (*Sollins* et al., 1993). Annual climatic means are about 25° C and 3720 mm precipitation (*Instituto Meteorológico Nacional*, 1988). The dry season extends roughly from December to April, and the variation in air temperature is minimal throughout the year.

One experimental site, Las Vegas annex, is located on one of those alluvial terraces at the confluence of the Viejo and Sarapiqui rivers,

6

about 15 m above the dry season river water level. The area had an original vegetation cover classified as wet tropical forest (*Hatshorn*, 1983), but had been converted in the 1950's to cacao cultivation, a condition in which it remained for many years until abandonment, ca. 1980 (*Griffiths* et al., 1993). In 1991 the area was cleared to bare soil for the establishment of the Huertos silvicultural experimental plots. The marginal buffer zones among Huertos plots were left to regrow with wild pioneer plants. A regrowth strip, localized on the west side of the Sendero Las Vegas, at approximate position in the La Selva GIS coordinates of -50/-375, was chosen for the experiment. The regrowth was primarily two species of fast-growing shrubs, forming a dense two meter tall cover that was clear cut to bare soil, without removal of roots, one week prior to the beginning of this experiment.

The second experimental site, *Finca* (ranch) Flaminia is located on the slope of a clayey terrain developed possibly from a higher river terrace. The finca had been under long term pasture until abandonment several months prior to the experiment. An area near and to the south of the new road to San José (Rio Frio), approximate position in La Selva GIS grid of -350/1250, was chosen for the experiment. The site was covered with 1 m tall grass that was cut down and the soil left bare. The

Flaminia experiment site was cleared and established three weeks before beginning experimental work.

The sandy lower-terrace soil in Vegas (Bambu consociation) is an andic fluventic Eutropept, rich in exchangeable bases, whereas, the clayey pasture soil in Flaminia is an upland with more weathered soil, poor in bases, and not classified but possibly a typic Tropohumult (*Sollins* et al., 1993) or an oxic Humitropept (*Reiners* et al., 1993), based in its physiographic position. Selected data from the studied soils is presented in Table I.1. *Sollins* et al. (1993) further describe the soils of La Selva and the region.

Experimental Design

Each of the two experimental sites (except for Event #2 in Flaminia) had one 3.2 x 3.2 m square plot subdivided into four 2.56 m^2 sub-plots (treatments). Each sub-plot was a 1.6 m square with four basic components or installations (Figure I.1): one PVC ring or collar inserted approximately in the center of the square; one battery of stainless steel soil-gas-phase probes for sampling at various depths, and installed to one side of the collar close to the merge of the four sub-plots, or proximal edge, and extending under the collar; one battery of tensiometers also for

8

sampling at various depths, and installed on the one distal or outer edge of the sub-plot, pointing to the collar; and one soil sampling soil pit lying outside the other distal edge, with the sampler operating towards the collar.

The simulated rain events were water and solution additions using a backpack sprayer and a garden watering can. All the nitrogen and carbon sources (except for dry urea in Flaminia) were dissolved immediately before irrigation in pre-stored rain water. The water or solutions were sprayed evenly onto the sub-plots over a period of 30 minutes so that they would percolate into the soil without forming standing water. The time-step used in the experiments for measurements were irregular, but followed a general scheme. For each simulated rain event, or solution addition, measurements were done at time zero, which was immediately preceding the additions, and then 30 minutes, 2, 4, 8 hours, and one day after additions, and daily thereafter, until the next rain event or completion of the experiment.

For Event # 1 at both sites (Tables I.2 & I.3), there were two fertilizer treatments and water alone as a control. The fertilizers were sodium nitrate ($NaNO_3$) at a level of 50 kg N $\cdot$ ha^{-1} as the first fertilizer

9

treatment, and $NaNO_3$ at 50 kg N $\cdot$ ha^{-1} plus glucose (dextrose, α-D(+) $C_6H_{12}O_6$) at a level of 250 kg C $\cdot$ ha^{-1} as the second treatment. The 5:1 C:N ratio used to obtain denitrifying potential was similar to those used in soil core incubation studies (*Parsons* et al., 1993; *Schuster* and *Conrad*, 1992). In Vegas there was also one dry control, and in Flaminia there was one glucose only treatment, at a level of 250 kg C $\cdot$ ha^{-1}. Events #2 and #3 in Vegas were a continuation of the observation of treatments from Event #1 with supplemental water additions on the two fertilizer treatments and the water control.

Event #2 in Flaminia had a different and simplified treatment layout. At a location within ten meters from the main plot (Event #1), seven collars were installed in a line, each in the center of a 0.5 x 0.5 m square plot. All the procedures for adding the solutions onto the plots were similar to that described above, except for the dry urea treatment where the urea salt (CH_4N_2O) was sprinkled over the dry soil one day before the irrigation in a manner similar to local agricultural practice. Carbon and nitrogen combinations and levels in the seven treatments can be seen in Table I.3. The extract of litter constituted an aqueous extract of forest-floor organic litter (from the rain-forest in the area) that was ground into a fine powder, agitated with deionized water for 1 hour, let rest for another hour, and then centrifuged at 10,000 rpm for 5 min. The

10

supernatant was then refrigerated until use. The resulting dark brown solution was used to simulate drainage through a soil litter layer.

Field Sampling

The enclosure technique used to quantify trace-gas exchange between soil and atmosphere has been widely used and discussed at length by *Hutchinson* and *Mosier* (1981). In this study, the two-part static vented chambers consist of a 25 cm internal diameter, 10 cm tall, polyvinylchlorine (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 fits 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 was greased lightly with silicon grease (Apiezon) and the collar capped tightly with chamber-top. Gas samples, withdrawn through an injection port, were collected using 20 ml nylon syringes (S.E.S.I., VWR Scientific) fitted with butyl rubber o-rings, and polypropylene stopcocks (Baxter Scientific), at 1, 7, 14, 21 and 28 minutes after closure. Each five syringe sample set constituted one flux measurement, after which the chamber closure was opened. Air temperature was taken during the sampling.

Nitrous oxide flux was calculated by regressing the N_2O mixing ratio linear change over time in the chamber enclosure (*Keller* et al., 1986).

One week prior to the experiment the collar was inserted approximately 2 cm in the top soil. Problems reported by *Matson* et al. (1990) associated with increased gas production in rainforest soils due to early insertion of rings onto the soil should not be a matter of concern at these sites, because there was no root mat covering the soil and preliminary tests in nearby forest sites (*Keller* and *Reiners*, 1994) did not indicate an insertion effect.

The sampling of soil-gas was carried out using horizontal probes made of stainless steel tubing (3.17 mm OD) formed in an L shape, installed adjacent to the PVC collar, at depths of 2, 5, 10, 20, and 40 cm (Figure I.1). The drawing portion of the probe's tubing, approximately 10 cm long, had 20 small holes drilled in its 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 cutoff hypodermic needle (also with 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. On the slip lock end, a plastic

12

cap was used to seal the probe from the atmosphere and dirt during the intervals between sampling.

To monitor the total soil water potential (matric, pressure, gravitational and osmotic), porous-cup tensiometers (1 cm OD by 10 cm long sensing porous-cup; 1 bar air entry value) were installed horizontally in the soil close to the collars [about 25 cm away]. They were placed at the same depths as the gas probes but offset laterally to avoid interference. The water tension inside the tensiometers was measured at each time step using a calibrated electronic pressure transducer (Soilmoisture, CA) hooked to an ammeter. Gravimetric soil moisture was measured on all soil samples collected for chemical analysis.

Samples were collected for each time step, each treatment, and each depth for monitoring soil chemistry. Soil samples were extracted using a 25.40 mm OD steel tube soil sampler (Soilmoisture,CA). The sampling scheme in the immediate vicinity of the experimental plots (Figure I.1), consisted of digging one small pit (30 cm wide, 50 cm deep and 1m long) for each treatment. The samples were then drawn horizontally, within the pit, from under the experiment area at the same depths as those used for gas probes and tensiometers. The amount of earth collected corresponded to from two to three loads of the sampler, or

13

about 200g. Soil samples were kept in plastic bags for few hours and thereafter frozen in the same bags [-18° C] for variable periods of time, until extraction could be carried out.

Laboratory Analysis

Nitrous oxide was determined for 2 ml sub-samples of the 20 ml field samples, using a 8A Shimadzu gas chromatograph fitted with a stainless steel (3.2 mm OD by 2 m) column, packed with 50-80 mesh Porapaq Q, and a ^{63}Ni electron capture detector. Operating conditions were: column temperature, 63° C; electron capture detector temperature, 330° C; P5 mixture (95% Ar with 5% CH_4) carrier gas with a flow rate of 30 ml · min^{-1}. N_2O and CO_2 were separated, but only N_2O mixing ratios were quantified. Oxygen, hydrocarbons, CFC's, etc. were removed from the carrier gas with a mol-sieve purifier filter. Water vapor was removed from all samples with a pre-column of indicating moisture absorbent (Aquasorb^{TM} - Mallinckrodt 6063). Standards (nitrous oxide in dinitrogen gas mixture) used in the analysis (343.8, 543.7 and 808.7 ppbv; Scott Specialty Gases) were calibrated against NOAA (Nitrous Oxide and Halocarbons Division, Climate Monitoring and Diagnostics Laboratory, Boulder, Colorado) secondary standards.

The samples were held in the sampling syringes an average of 21 hours before being analyzed. Loss rates for every syringe used in the experiments were determined by leak tests and the values for analyzed N_2O mixing ratios were corrected for any diffusional leaks (see Appendix A for detail in method). Soil nitrate (NO_3^-) and ammonium (NH_4^+) concentrations were determined colorimetrically in saline soil extract (*Keeney* and *Nelson*, 1982) using an autoanalyzer (Technicon Traacs 800). Soil total elemental carbon and nitrogen were determined from oven dried and well ground soil sub-samples (*Nelson* and *Sommers*, 1982) through a flash dry combustion elemental analyzer (Carlo Erba).

Results and Discussion

Soil Time Series Profiles

Figures I.2. and I.3. show time series data on experiment results for N_2O fluxes and soil-gas-phase N_2O mixing ratios, together with soil water tension and soil NO_3^- concentration profiles.

Vegas Control Treatment . At the sandy Vegas site, control treatment N_2O fluxes remained close to background levels throughout the period (Figure I.2.A). There was some rainfall three days before the

15

beginning of the experiments in Vegas, and the residual effects of that moisture in the soil can be seen in the initial days as low soil water tension and elevated N_2O mixing ratios at depths of 5, 20 and 40 cm. The small oscillation in the background flux at the surface reflects these changes in the soil profile. As the soils dried due to dry weather until day 20, the soil moisture to depths of 20 cm decreased progressively to tensions in excess of 1 Bar (the limit of the tensiometers). Some low rainfall (3 mm) at the end of the experiment resulted in increased profile mixing ratios and fluxes. Changes in nitrate concentrations in the soil profile did not directly reflect changes in the associated N_2O mixing ratios. This could indicate that nitrification is the main source for N_2O background emissions rather than denitrification, or, that nitrous oxide is diffusing up from deeper layers where it would have been produced either by denitrification or nitrification. Degassing from ground water is also a possible source. There is a consistent upward gradient in soil N_2O mixing ratios at all sampled depths, which supports the hypothesis of production at depth (for a review of denitrification in subsurface environments see *Rice* and *Rogers*, 1993).

Vegas Water Treatment. The time series of water tension profiles, which are averages of three separate measurement sites, indicate clearly the effects of each simulated rain event and subsequent drying

16

period (Figure I.2.B). The first event quickly lowered water tension to a depth of 10 cm, and after some lag also lowered tension slightly at 20 cm, but did not influence deeper layers.

If water seems so clearly associated with increased gas phase N_2O mixing-ratios in the upper soil layers, how can be explained, before wetting, the proportionally equivalent peaks at depth 20 and 40 cm? *Griffiths* et al. (1993), incubating similar soils to study denitrification potential, found that N_2O produced by denitrification was highest in O_2-free headspace. Considering that water temporarily fills up pore space in the upper soil layers, diffusion of atmospheric O_2 into the soil could diminish, increasing the probability of a larger anaerobic fractional volume developing (*Davidson*, 1992; *Rudaz* et al., 1991; *Mosier* et al., 1986), therefore allowing denitrification to proceed faster in layers beneath the saturated zone. Another possible explanation is that nitrous oxide actively produced in upper layers diffuses downward. Gas diffusion from below would be inhibited. Corroborating the argument of diffusion from upper layers and consequently low denitrification at depth, the soil nitrate data showed no change at a depth of 40 cm. The nitrous oxide peak for all depths happened around 8h after the simulated rain, indicating a simultaneous response (no lag determined by diffusional constraints).

17

Even though the magnitude of the second simulated rain event was the same as the first, the soil was much drier at that time. The wetting front percolated quickly to 5 cm, but moisture was soon lost to evaporation. The water added to the top 5 cm in this event kept water tension low until the third event, when a three-fold larger simulated rain percolated quickly to the drier layers underneath, reaching 20 cm, and producing strong pulses of N_2O to that depth. Lower water tensions might have induced lower O_2 partial pressure in the microbial microsites for a longer time than in previous events, leading to a further reduction of nitrous oxide (already diffused from the liquid into the gas-phase) to N_2. In the "leaky-pipe" model (*Firestone* and *Davidson*, 1989) this would mean a regulation at the third level, where diffusion and consumption of N_2O occur prior to escape from soil into the atmosphere. That would explain the sharp peaks at depths 5 and 10 cm. From 20 cm downward, there could be less consumption after the peak, which would explain the skewed tails for those depths. The bigger pulses of soil gas-phase N_2O, compared with event 1 and 2, did not translate into bigger emissions at the soil surface.

The nitrate data showed consistent patterns, especially the patterns associated with water additions and resulting nitrous oxide pulses. A progressive increase during interpeak or low flux periods, like

18

the one shown at 2 cm, could indicate two main processes: first, nitrification occurring during periods where O_2 is more plentiful, and also enhanced by moderate wetness; second, upward movement of soil solution from deeper layers to the surface by capillarity action, due to surface evaporation, would result in accumulation of nitrate at the uppermost layer and progressive loss of nitrate in deeper layers. The NH_4^+ concentrations showed a remarkable similarity with NO_3^-.

There were nitrate oscillations associated with the N_2O pulses. NO_3^- suddenly decreased in concentration, followed immediately by quick increases until NO_3^- stabilized around background levels. This was similar to what was observed in tropical dry forest upon wetting (*Davidson* et al., 1993). This could suggest that with increased moisture, microbial communities bloom, consuming and immobilizing nitrate from the soil solution, leading to a decrease in nitrate concentration. Then, either due to exhaustion of substrate or some other regulating factor, the recently grown biomass dies, liberating part of the nitrogen that was immobilized by the microbial mass. The NH_4^+ data corroborated that interpretation, assuming that increased concentrations reflect mineralization. The subsequent stabilization in the nitrate concentrations during the dry periods suggested that the microbial community had

19

reached a quasi-equilibrium. The detailed dynamics of the soil microbiology was beyond the scope of this study.

Vegas Nitrate-N Treatment. In this treatment the emissions from the soil surface were very consistent with changes in soil gas mixing ratios (Figure I.2.C). There was an unexpected increase in nitrous oxide and nitrate at 40 cm prior to any change in soil moisture. In this first amendment, the top four layers showed a large increase in nitrate with the arrival of a moisture front. The first peak of mixing-ratios associated with nitrate additions exceeded the water alone treatment throughout the profile. The extra nitrate supplied clearly stimulated higher denitrification activity. This is an indication that the soil ecosystem was limited in nitrogen, a result corroborated by soil core nitrate addition experiments with pasture and forest soils in the same region (*Parsons* et al., 1993), but contradicting results of another study (*Keller* et al., 1988).

Vegas Nitrate-N + Glucose-C Treatment. After addition, the profile of N_2O mixing-ratios (Figure I.2.D) indicated that denitrification was enhanced 30 times above levels measured in other treatments. The nitrate profile showed nitrate concentrations oscillating abruptly during gas peaks, as in other treatments which received water. Most of the

20

nitrate was consumed during and soon after Event #1 at depths of 5 and 10 cm, remaining constant in deeper levels. This suggests that microbial activity is most intense in those two layers, which increases the likelihood that N_2O is actively produced there (*Firestone* and *Davidson*, 1989), diffusing upward and downward. In the surface layer, nitrate remained high, possibly due to the addition in the amendment, but also possibly due to the progressive loss of water by evaporation during the first interpeak period. Between events 2 and 3 nitrate progressively dropped to almost zero mg · kg^{-1} of dry soil, possibly due to higher soil moisture conditions than the first interpeak.

Nitrous oxide mixing-ratios reached in the first event of the nitrate + glucose additions were 25, 40, 14, 5 times higher in layers 2, 5 & 10, 20, and 40 cm, respectively, than in equivalent layers during the nitrate treatment. The second event had mixing-ratios values only 1.2 to 1.7 times higher than the corresponding nitrate-only additions. The third event had some mixing-ratios concentrations which were even smaller than in nitrate addition. This overwhelming response to glucose after an initial application, primarily in the layers wetted by the simulated rain, indicated the high potential for denitrification in this soil. More interesting to this study was the temporary nature of the response to nitrate + glucose addition suggesting strong carbon limitation.

Flaminia Water Treatment. Soil gas nitrous oxide concentrations in the Flaminia pasture clayey soil (Figure I.3.A.) showed a four-fold faster and 5-10 times larger response than the equivalent treatment on the sandy soil at the Vegas site. The quick and homogeneous drop of soil moisture after a simulated rain event throughout the profile indicated higher infiltration, probably due to macropores. Except for the uppermost few centimeters which became drier, the rest of the measured profile behaved the same with respect to moisture. Because of scattered rainfall during Event #1 at Flaminia, it is not possible to compare background production with events 1 and 2 of Vegas. Nitrous oxide formed after the first brief peak, accumulated progressively at depth. Because the rain events happened during nights, peak sampling (30 min., 2, 4, and 8h) was not done. Lack of sampling of the N_2O peaks makes it hard to evaluate the impact on the soil N_2O mixing-ratios of different magnitudes of natural rainfalls.

A few observations should be noted about the water treatment results. After 19 + mm of rain accumulated in the third day, twice as much as the amount of the simulated rain in Event #1, there was a drop in N_2O mixing-ratios at almost all depths, associated with a big increase in NO_3^- concentration. On the fourth day, after more 78 mm of rain, the

situation reversed, with gas accumulating in the profile, and NO_3^- substrate diminishing abruptly. The first drop in gas mixing ratios was similar to the drop that happens after each episodic pulse peak, with the increased nitrate being the result of the increased mineralization-nitrification associated with the enhanced soil moisture. The increase in nitrate is associated with the first peak for the three uppermost layers, and is relatively proportional to the amount of water going through the soil. The increase in mixing ratios by the fourth day was probably caused by denitrification soon after the natural rain, which would also explain the drop in concentration of the nitrate substrate.

Flaminia Nitrate-N Treatment. The nitrate treatment (Figure I.3.B) produced a significantly different response compared to the water treatment. Mixing ratios of N_2O are generally higher than those produced by water, but the dynamics of production and consumption were not symmetric as they were at the Vegas site.

After the amendment, nitrate increased immediately in the uppermost layer, and showed a progressive time lag for the increase at deeper levels. In contrast to the water treatment, nitrate in the three intermediate layers that accumulated during the first day began decreasing on the second day, reaching its lowest concentration in the third day, and

recovering by the fourth day. As seen in Vegas, nitrate in the surface soil remained high as the soil dried, but in contrast to Vegas, when more water was added, nitrate concentrations decreased and did not recover. The likely explanation is leaching of nitrate from the surface layer into layers beneath by the added water. The results of this experiment, in spite of the complicating factor of natural rainfall, strongly support the inference that nitrate dynamics in the soil profile, if studied in conjunction with soil moisture and soil N_2O mixing ratios, can be a useful indicator of conditions controlling soil N_2O production.

Flaminia Glucose-C Treatment . The Glucose-C treatment (Figure I.3.C) was unique to the Flaminia site, and served to separate the effect of carbon alone from that of carbon plus nitrogen. The most evident effect of carbon alone, besides the brief enhancement of N_2O in the profile following amendment, was the consumption of nitrate to the lowest concentrations observed in any of our treatments. Similar to Nitrate-N + Glucose-C at Vegas, the N_2O production was most intense in the three upper layers. In these layers, nitrate reached zero at the same time N_2O mixing-ratios were peaking (at 4 h), indicating a shortage of nitrogen substrate for denitrification. If compared with nitrogen alone, the glucose treatment produced 3 to 30 times higher N_2O mixing-ratios. Glucose is thus clearly the main driver of nitrous oxide production

24

associated with these amendments. But glucose addition alone will run the system out of nitrate after only 4 hours of immobilization/denitrification.

Flaminia Nitrate-N + Glucose-C Treatment. The profile results for this treatment (Figure I.3.D) confirmed the expectation from the results of the carbon alone treatment that an additional supply of N substrate would increase the production and accumulation of N_2O in the soil. The peaks in soil mixing-ratios were equivalent in some layers, and much bigger in others, compared to those resulting from the Glucose-C treatment. The enhanced nitrous oxide peaks lasted much longer than in the glucose amendment. But even in this experiment, there seemed to have been some nitrate limitation, for at 10 cm, one very low nitrate concentration point coincided with a decrease in the nitrous oxide mixing ratio (and also coincided with an increase in ammonium concentration). It seems clear, as in the water treatment, that nitrate was leached out of the surface layers into lower ones after an intense rainfall. However, it is unclear why, between 2 and 8 h, there was a plateau in the measured nitrate for the upper two layers and in the N_2O flux at the surface.

25

N_2O mixing ratios in the nitrate + glucose treatment are four to twenty five times larger than the ratios for the equivalent treatment at Vegas (Figure I.2.D). The enhanced peaks also lasted longer than at Vegas. In Flaminia, there was more soil moisture and that moisture was better distributed in the soil, but nitrate concentrations were similar. The key, we believe, were soil textural and structural differences (Table I.1). Larger bulk density (Flaminia pasture) with smaller porosity can influence infiltration and percolation rates, and very probably gas diffusivity rates (*Reiners* et al., 1993). The sandy Vegas soil had potentially much less space in micropores comparative to the clay soil in Flaminia. Consequently, the anaerobic fractional volume of the former could be much smaller.

As shown by *Burton* and *Beauchamp* (1994), the measurement of mixing-ratios gradients for these soil profiles proved useful in delineating the timing and location of gas production. The general close relationship between patterns of N_2O mixing-ratio dynamics and water infiltration with substrate amendment, suggested an overwhelming importance of episodic production in the upper soil layers, over production in deeper soil layers, in controlling the measured emissions.

26

Episodic Emission and Fluxes to the Atmosphere

The cumulative curves (Figures I.4 and I.5), or running totals, are integrated summations of interpolated intervals of the minimum sampling period (30 min.) for the entire event period. The shape of the curves allows inferences about the importance of the irregularities in trace gas emission (episodic pulses, for instance) for the temporal accumulation of emissions. A straight line indicates that emissions are uniform over time, a condition where background flux monitoring suffices to making good estimates of real emissions. The higher the departure from a straight line, the worse the estimates of emissions based in background fluxes. In Vegas Water Event #1 (Figure I.4.A), the running total shows that the accumulation of emitted gas is progressive, and oscillating, well in accord with the fluctuation of the background fluxes. Even though a peak pulse can be identified soon after the simulated rain, its contribution to the progressive accumulation is small. In other situations, like the Vegas Water and Nitrate-N in Event #2 (Figure I.4.B), the peak is clearly distinguishable; but it is followed by a slight depression in the background flux making its contribution to the running total imperceptible, and consequently less important in the case of estimating real long term emissions. When the running total curve starts bulging upward, like Vegas Nitrate-N, Event #1 (Figure I.4.A), where 32 % of the total N_2O emission over 9 days was emitted during 1 day (peak duration),

27

or in an extreme example in the same figure with Nitrate-N + Glucose-C where 96 % of all gas emitted occurs during the first day, then the emission regimen is very irregular.

Vegas . The effect of irrigation and amendment on the nitrous oxide production was most dramatic in the short term episodic peaks that followed additions. The simulated rainfall events always produced episodic emission pulses, as well as increased overall production of N_2O. The effect of water alone could be seen in the water treatment at Vegas (Figures I.4.A to I.4.C). Twenty-five g N_2O-N $\cdot$ ha^{-1} (Figure I.4.C and Table I.4 Totals) was emitted [averaging 1.2 g N_2O-N $\cdot$ ha$^{-1} \cdot$ d^{-1}], after three simulated rain events over a 22 day period. The dry Vegas control treatment emitted 14 g N_2O-N $\cdot$ ha^{-1} [0.6 g N_2O-N $\cdot$ ha$^{-1} \cdot$ d^{-1}] over the same period. The episodic pulses of N_2O associated with water additions contributed approximately 20% of the total flux. The approximately 20 g N_2O-N $\cdot$ ha^{-1} attributable to background flux is still 1.4 times larger than the dry control background flux. This indicates that other nitrous oxide producing processes such as nitrification benefited from increased soil moisture. The emission pulses in this treatment, 1 g N_2O-N $\cdot$ ha^{-1} for the first, and 2 g N_2O-N $\cdot$ ha^{-1} for the last two were evidence that water additions cannot be related to N_2O emissions in a linear way.

The nitrate treatment, with a 50 kg N · ha^{-1} amendment, emitted

45 g N$_2$O-N · ha^{-1} [2.0 g N$_2$O-N · ha^{-1}· d^{-1}] in Vegas (Figures I.4.A to

I.4.C) or 1.8 times the gas emitted by the Vegas water-alone treatment,

after three simulated rain events over a 22 day period. That represented

approximately 0.1% of the added nitrogen, or 4.7% if the system emitted

at the same weekly rate during a full year. Episodic emissions accounted

for 22% of the total flux in this treatment.

The treatment nitrate + glucose (Figures I.4.A to I.4.C) emitted

303 g N$_2$O-N · ha^{-1} [13.7 g N$_2$O-N · ha^{-1}· d^{-1}]. These results indicate a

severe carbon limitation on denitrification in this soil, or, perhaps, that

glucose can stimulate aerobes to consume most available soil oxygen

which increases the anaerobic fractional volume in the soil stimulating

denitrification (*Mosier* et al., 1986). Stoichiometric calculations showed

that if glucose was totally respired aerobically, the amount added to the

soil (250 kg of dissolved C · ha^{-1}) would have been enough to consume all

of the atmospheric oxygen from the soil gas-phase down to almost 1 m

deep, provided there was no diffusive replenishment from the atmosphere.

The short time frame of intense reducing conditions here is the key to

understanding why N$_2$O emissions were so enhanced. This treatment

emitted 0.6 % of the added N. In this treatment 91 % of the N$_2$O was

29

produced during the episodic pulses, contrasting with the 22 % in Nitrate-N treatment (Table I.4).

Flaminia Event #1 . The water treatment at Flaminia (Figure I.5.A) emitted 116 g N_2O-N · ha^{-1} in 6 days. This was 17 times more N_2O-N than the observed in the same treatment at Vegas. Considering that this kind of soil covers much larger areas and its use as pasture is much more common, these high emission numbers assume special significance (*Reiners* et al., 1993; *Keller* et al., 1993; *Luizão* et al., 1989).

The nitrate treatment (Figure I.5.A), with a 50 kg N · ha^{-1} amendment, emitted 374 g N_2O-N · ha^{-1} [61 g N_2O-N · ha^{-1}· d^{-1}]; this represented 0.7 % of the added nitrogen. That emission is proportionally 30 times higher than the gas emitted at the Vegas nitrate treatment, and 3.2 times the gas produced at Flaminia water treatment. The level of N fertilization used in this experiment is relatively low compared to that used for agriculture in the area (e.g. banana plantations typically use 300 kg-N · ha^{-1}). Emissions associated with episodic fluxes increased from 15 % of total flux (Table I.5) in the water treatment, to 36 % in this treatment.

30

The glucose treatment at Flaminia (Figure I.5.A), emitted 1,273 g $N_2O-N \cdot ha^{-1}$ [208 g $N_2O-N \cdot ha^{-1} \cdot d^{-1}$]. This clay soil response to glucose was 11 times larger than the water treatment and 3.4 times larger than the nitrate treatment. The nitrate + glucose treatment in Flaminia (Figure I.5.A) emitted 3,336 g $N_2O-N \cdot ha^{-1}$ [545 g $N_2O-N \cdot ha^{-1} \cdot d^{-1}$]. This is 20 % less than would be predicted by a simple multiplication of the individual treatments. The emissions in this treatment were 38 times larger than the equivalent treatment in sandy Vegas soil. The episodic emission of nitrous oxide in the glucose treatment produced 91% of the measured emissions, while in the glucose + nitrate treatment the episodic emission was 39%.

Flaminia Event #2 (Substrate search for N_2O-production). This series of tests cannot be directly compared with the ones in Event # 1 in Flaminia, because in Event #2 the experiments were protected from rainfall. These results were useful to show how a succession of simulated rain events with controlled drying periods can precisely define the temporal emission patterns of transient nitrous oxide pulses.

Because glucose is not a common amendment in fertilized soils, a mix of organic compounds extracted from decaying forest litter layer

31

[litter extract] was used as a source of carbon for experimentation. The results, 121 g N_2O-N $\cdot$ ha^{-1} [20 g N_2O-N $\cdot$ ha^{-1} $\cdot$ d^{-1}] (Figure I.5.C), is only marginally larger than the water treatment in Event #1 of Flaminia. The emission dynamics of this natural carbon treatment were significantly different from the water treatment; 72 % of N_2O was emitted during the first episodic emission, compared with 15 % during the second episode.

Urea, a commonly used fertilizer, was also used as an experimental treatment. Urea produced a depression in emissions compared with the water treatment, 101 g N_2O-N $\cdot$ ha^{-1} [17 g N_2O-N $\cdot$ ha^{-1} $\cdot$ d^{-1}] (Figure I.5.B). The episodic emission of nitrous oxide accounted for 31 % of total emissions.

Litter extract combined with nitrate produced 296 g N_2O-N $\cdot$ ha^{-1} [48 g N_2O-N $\cdot$ ha^{-1} $\cdot$ d^{-1}] (Figure I.5.C), 2.4 times higher than litter extract alone. Litter extract with Urea-N produced 207 g N_2O-N $\cdot$ ha^{-1} [34 g N_2O-N $\cdot$ ha^{-1} $\cdot$ d^{-1}] (Figure I.5.C), 30 % less N_2O than nitrate alone, which indicates that urea is not used as readily as nitrate as a substrate for denitrification. Urea applied with glucose, produced 539 g N_2O-N $\cdot$ ha^{-1} [88 g N_2O-N $\cdot$ ha^{-1} $\cdot$ d^{-1}] (Figure I.5.B), 1.8 times more than litter extract + nitrate. Dry urea (Figure I.5.B), sprinkled as a conventional fertilizer

32

over the soil, and watered one day after, produced results similar to the dissolved urea treatment. Finally, the Nitrate + 1/2 Glucose, could not meaningfully be compared with the Nitrate + Glucose of the Event #1 in Flaminia, due to the various rain events in Event #1. Noteworthy in this treatment was the sharp peak without the top plateau which occurred in Event #1. If the pulse was so brief, either soil moisture was diminishing quickly after the simulated rain event, or, as was the case for treatment Glucose in Event #1, the system was running out of nitrogen substrate, consequently shutting off denitrification .

Importance of Episodic Nitrous Oxide Production

The events in the experiments for both sites of this study lasted between 147 to 214 hours, or roughly one week, which is equivalent to the time period of recurrent sampling in typical long term trace gas emissions survey studies (e.g. *Keller* et al., 1993; *Weier* et al., 1991; *Luizão* et al., 1989). The hypothesis was that random or chronological periodic sampling might underestimate total N_2O fluxes to the atmosphere from tropical soils if they miss the transient pulses associated with rain events, liquid amendment or irrigation.

33

In order to assess the importance of peak magnitude with peak duration during the episodic emission of N_2O, we calculated a peak intensity parameter as follows:

$$\text{Peak}_i = \frac{Peak_{Pg}}{Event_{Pg}} \cdot \frac{Event_{Tp}}{Peak_{Tp}}$$

where $Peak_{Pg}$ and $Event_{Pg}$ are the gas produced during the peak and during the whole event including the peak, respectively; $Peak_{Tp}$ and $Event_{Tp}$ are the time periods of the peak and the whole event, respectively. Peaks in this study were defined arbitrarily in the N_2O flux time series as the part where fluxes depart abruptly from the background. This definition of peak could be made more objective and consistent using mathematical concepts of threshold and peak width limits borrowed from fields like chromatography.

Peak intensity is a dimensionless measure of how many times trace-gas emissions during the peak period are proportionally larger than emissions during the background period. Peak intensity also gives an inverse measure of probability for a random periodic sampling to catch those brief fluctuations [which in turn can also be random with respect to the sampling scheme]. Noting transient bursts of emissions with one, few

34

or many flux measurements (inadequate to define pulses), like those in the background of Flaminia's treatments for Event #1 (Figure I.5.A), intermingled with non-monitored rain events, contribute to increase the unexplainable scatter [error] in the data.

The higher the value of peak intensity, the worse the underestimate of emissions if only background non-peak emissions are sampled. The closer its value to the unity, the less important will be the contribution of the peak pulse to the average flux, which means closer to background, or broader the peak width. The critical realization is that the nature of the transient pulse sets apart the time-scale of this phenomenon, if compared with the long term background emissions. Moreover, those incompatible time hierarchies cannot be mixed without introducing big errors in the estimates.

When the right sampling strategy is devised, however, the flux data will reflect closely the real emission behavior of the soil system concerned. And as some of the results from this study suggest (Figures I.4.A, I.5.A, I.5.B & I.5.C; Tables I.4 & I.5), there can be a sizable if not overwhelming participation of transient bursts of emissions in the total 'real' emissions over few weeks. The realization of the importance of episodic emissions associated with rainfall is not new (e.g. *Bowman* et al.,

35

1993; *Davidson* et al., 1993; *Schimel* et al., 1988). However, to date, few long term studies have attempted to quantify the importance of episodic emissions in the total emissions.

Conclusions

The series of experiments with the two volcanic tropical soils reported in this paper indicate that water additions and rainfall set the soil system to start emitting N_2O in intense pulses. The data in the soil profiles brought strong evidence of the connection between the movement of the wetting front into the soil and the change of N_2O mixing ratios at that level. Background N_2O emissions were found to respond differently depending on whether the treatment was dry, wet, fertilized, and with which kind of fertilizer. Soil extractable inorganic nitrogen showed remarkable and somewhat consistent patterns of oscillation associated with N_2O production and emission in transient pulses. The patterns associated with background also remained consistent with the conditions of the respective soil layer in many situations, even though the biogeochemical interpretation could not explain all the patterns observed.

36

The fact that both nitrogen and carbon produced intense responses suggests that these soils were limited in both substrates. However, in only one instance one of these substrates (nitrate) was observed to have been depleted as a result of supply of the other substrate (glucose). Another hypothesis, somewhat corroborated by the extraordinary response of these soils to glucose addition, is the limitation by environmental conditions on the use of these substrates, for example, redox potential. In such cases, the system can become limited in both substrates, provided the environmental conditions allow their use. In some situations, as during glucose addition, the carbon substrate itself became a source of change in the environment that then triggered further carbon usage, as well as use of other substrates optimally until exhaustion. Soil textures, apparently connected with pore size distribution, determined changes up to twenty fold in total gas emitted, which could mean that broader generalizations based on a few field measurements can be one order of magnitude wrong. Pulses of production can develop quite superficially in the soil, especially between 5 to 20 cm, and can develop to a maximum emission strength [which can be several orders of magnitude greater than the background level] within the range of 30 min. to 8 hours. The episodic part of the flux occurring in brief transient bursts of emissions, usually taking place within a day, can account for up to 98 % of total emissions produced in a week with one

37

moderate rain event. Those episodic pulses associated with rain, liquid amendment or both, varied greatly in intensity and duration among treatments.

If the frequency and distribution of rainfall and amendments to tropical soils is shown to generate pulses throughout the year as intense as the pulses measured in these experiments, then the global estimates of N_2O production will have to take into consideration this episodic production in order to account for the missing source.

Table I.1.   Some physical and chemical properties of the studied soils

Site	Depth (cm)	Bulk density (g.cm-3)	Textural Analysis (%) Sand	Silt	Clay	pH (H2O)	Mineral N (mg N Kg-1 soil) NO3-N	NH4+-N	Total N (%)	Total C (%)
1	2	0.7	66.5	26.5	7.0	6.4	19.6	12.6	0.4	3.9
	5	0.8	66.5	21.5	12.0	6.5	20.8	7.8	0.2	2.4
	10	0.9	69.5	18.5	12.0	6.6	5.8	1.4	0.2	2.0
	20	1.0	70.0	15.0	15.0	6.5	1.7	0.9	0.2	2.0
	40	1.0	66.5	23.5	10.0	6.4	0.5	0.2	0.1	0.7
2	2	1.4				4.6	12.1	20.3	0.4	3.7
	5	1.5				4.7	6.5	3.3	0.3	3.3
	10	1.5				4.8	8.1	4.6	0.3	2.8
	20	1.5				4.9	1.3	1.3	0.2	1.7
	40	1.4				4.9	0.5	1.8	0.1	1.3

1 Vegas
2 Flaminia

Table I.2. Vegas Site Treatments

Treatment Plot	Event #1 22 mar 92	Event #2 2 apr 92	Event #3 9 apr 92
Control	none	none	none
Water	10 mm water	10 mm water	30 mm water
Nitrate-N	10 mm water + 50 Kg NaNO3-N/ha	10 mm water	30 mm water
Nitrate-N + Glucose-C	10 mm water + 50 Kg NaNO3-N/ha + 250 Kg Glucose-C/ha	10 mm water	30 mm water

40

Table I.3. Flaminia Site Treatments

Treatment Plot	Event #1 1 may 92	Event #2 25 may 92
Water	10 mm water	
Nitrate-N	10 mm water + 50 Kg NaNO3-N/ha	
Glucose-C	10 mm water + 250 Kg Glucose-C/ha	
Nitrate-N + Glucose-C	10 mm water + 50 Kg NaNO3-N/ha + 250 Kg Glucose-C/ha	
Dry Urea-N		20 mm water + 100 Kg Urea-N/ha
Urea-N		10 mm water + 50 Kg Urea-N/ha
Extract of Litter-C		10 mm Aqueous Extract of Litter-C
Nitrate-N + Extract of Litter-C		10 mm Aqueous Extract of Litter-C + 50 Kg NaNO3-N/ha
Urea-N + Extract of Litter-C		10 mm Aqueous Extract of Litter-C + 50 Kg Urea-N/ha
Nitrate-N + 1/2 Glucose		10 mm water + 50 Kg NaNO3-N/ha + 125 Kg Glucose-C/ha
Urea-N + Glucose		10 mm water + 50 Kg Urea-N/ha + 250 Kg Glucose-C/ha

Table I.4. Vegas episodic versus background N2O emissions

	TREATMENT	Event Period (hours)	Event Produced N2O-N (g/ha)	Peak Period (hours)	Peak Intensity	Peak Produced N2O-N (g/ha)	Peak Produced N2O-N (%)	Background Period (hours)	Background Produced N2O-N (g/ha)	Background Produced N2O-N (%)
Event #1	Control	214.8	3.7					214.8	4	100
	Water}	214.8	6.6	11.2	2.4	1	13	203.5	6	87
	Nitrate-N	214.8	15	30.4	2.3	5	32	184.4	10	68
	Nitrate-N + Glucose-C	214.8	280	30.4	6.8	269	96	184.4	11	4
Event #2	Control	168.1	2					168.1	2	100
	Water	168.1	13	11.2	2.3	2	14	156.9	11	86
	Nitrate-N	168.1	19	11.2	1.7	2	10	156.9	17	90
	Nitrate-N + Glucose-C	168.1	13	11.2	4.6	4	27	156.9	9	73
Event #3	Control	148.5	9					148.5	9	100
	Water	148.5	8	11.2	3.1	2	24	137.3	6	76
	Nitrate-N	148.5	14	11.2	2.3	3	18	137.3	11	82
	Nitrate-N + Glucose-C	148.5	12	11.2	2.6	2	20	137.3	10	80
TOTALS	Control	531.4	13.9					531.4	13.9	100
	Water	531.4	25.3	33.6	3.1	5	19.8	497.7	20.3	80.2
	Nitrate-N	531.4	45.2	52.8	2.2	10	22.1	478.6	35.2	77.9
	Nitrate-N + Glucose-C	531.4	302.9	52.8	9.2	275	90.8	478.6	27.9	9.2

42

Table I.5. Flaminia episodic versus background N2O emissions

	TREATMENT	Event Period (hours)	Event Produced N2O-N (g/ha)	Peak Period (hours)	Peak Intensity	Peak Produced N2O-N (g/ha)	Peak Produced N2O-N (%)	Background Period (hours)	Background Produced N2O-N (g/ha)	Background Produced N2O-N (%)
Event #1	Water	146.9	116	10.2	1.9	15	13	136.7	101	87
	Nitrate-N	146.9	374	10.2	2.5	64	17	136.7	310	83
	Glucose-C	146.9	1273	50.9	2.6	1158	91	96	115	9
	Nitrate-N + Glucose-C	146.9	4527	99	1.4	4165	92	47.8	362	8
Event #2	Dry Urea-N	146.9	193	10.2	10.8	145	75	136.7	48	25
	Urea-N	146.9	101	10.2	4.5	31	31	136.7	70	69
	Extract of Litter-C	146.9	539	26	5.1	485	90	120.8	54	10
	Nitrate-N + Extract of Litter-C	146.9	450	10.2	9.2	288	64	136.7	162	36
	Urea-N + Extract of Litter-C	146.9	121	10.2	10.3	87	72	136.7	34	28
	Nitrate-N + 1/2 Glucose-C	146.9	296	10.2	7.3	148	50	136.7	146	50
	Urea-N + Glucose-C	146.9	207	10.2	9.8	141	68	136.7	66	32

43

Figure I.1. Horizontal layout of the field experiment at Vegas and for Event #1 at Flaminia. Components were symmetrical for all treatments. Tensiometers and soil gas-phase probes were distributed vertically at depths of 2, 5, 10, 20 and 40 cm. Soil in the soil sampling zone was sampled horizontally from within the soil pit. At each time step a set of soil samples was collected at the same depths used for tensiomenter and gas sampling. For each subsequent time step, soils samples were collected on a vertical line parallel to the preceding samples. See text for detailed explanations.

44

Figure I.2.A. Vegas soil time-series data for dry Control treatment. N₂O exchange flux with the atmosphere is shown on top of the soil profile, associated with soil gas-phase N_2O concentrations, soil extractable NO_3^- and NH_4^+ and soil water tensions. An event refers to the addition of substrate and/or water to the experiment, and includes the subsequent drying period until the next event or until the end of the experiment. The summits of the N_2O peaks are labeled with exact flux or gas concentration values at that point in time (counted from the time of the addition event). Raingauge measured rainfall indicates total accumulated precipitation during measured interval.

45

Figure I.2.B. Vegas soil time-series data for Water treatment. Soil water tension represents average for all site-treatments which received water. Other features are the same as for figure I.2.A.

46

Figure I.2.C. Vegas soil time-series data for Nitrate-N treatment. Other features are the same as for figure I.2.A.

47

Figure I.2.D. Vegas soil time-series data for Nitrate-N + Glucose-C treatment. Other features are the same as for figure I.2.A.

48

Figure I.3.A. Flaminia soil time-series data for Water treatment. Other features are the same as for figure I.2.A.

49

Figure I.3.B. Flaminia soil time-series data for Nitrate-N treatment. Other features are the same as for figure I.2.A.

50

Event #1

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

3,500
3,000
2,500
2,000
1,500
1,000
500
0
-500

10 mm water + dissolved 250 kg/ha Glucose-C

3079.73 @ 2h

Rainfall

0.7mm   19mm   78mm   13mm

FLAMINIA
Glucose-C

Soil Depth (cm)

N_2O in the Soil Gas-Phase (ppmv) [thick line]

2
5
10
20
40

58.90 @ 4h

69.61 @ 4h

84.59 @ 4h

57.76 @ 4h

27.61 @ 24h

Soil NO_3^- [long dashed line] and NH_4^+ [line] (mg/kg of soil)

Soil Water Tension [short dashed line] (mBars)

0   1   2   3   4   5   6   <-Time (days)

Figure I.3.C. Flaminia soil time-series data for Glucose-C treatment. Other features are the same as for figure I.2.A.

51

Event #1

N2O-N Flux from Soil (g/ha.day)

2,500
2,000
1,500
1,000
500
0

10 mm water + dissolved 50 kg/ha NaNO3-N
+ dissolved 250 kg/ha Glucose-C

1938.05 @ 8h

0.7mm   Rainfall
19mm
78mm   13mm

FLAMINIA
Nitrate-N +
Glucose-C

Soil Depth (cm)

N_2O in the Soil Gas-Phase (ppmv) [thick line]

120
80
2   40
0

42.14 @ 8h

120
80   76.57 @ 8h
5   40
0

120
80   105.45 @ 8h
10   40
0

120
80   55.71 @ 24h
20   40
0

120
80   89.41 @ 24h
40
40
0

Soil NO_3^- [long dashed line] and NH_4^+ [line] (mg/kg of soil)

60
40
20
0

60
40
20
0

60
40
20
0

60
40
20
0

60
40
20
0

Soil Water Tension [short dashed line] (mBars)

160
120
80
40
0

160
120
80
40
0

160
120
80
40
0

160
120
80
40
0

160
120
80
40
0

0   1   2   3   4   5   6   <-**Time** (days)

Figure I.3.D. Flaminia soil time-series data for Nitrate-N + Glucose-C treatment. Other features are the same as for figure I.2.A.

52

Figure I.4.A. Vegas N_2O emissions for the four treatments in Event #1. The cumulative curves, or running totals, are integrated summations of interpolated intervals of the minimum sampling period (30 min.) for the entire event period. P.P.G. means peak produced gas; E.P.G. means event produced gas; P.I. means peak intensity (see text).

53

Figure I.4.B. Vegas N_2O emissions for the four treatments in Event #2. Other features are the same as for Figure I.4.A.

54

13— 14
11— 13
9— 12
7— **[Control]** 11
5— E.P.G.= 9 g/ha 10
3— 9
1— Rainfall 8
-1— 3mm 7
To Date P.G.= 14 g/ha 6
5

30 mm water

13— 26
P.I.= 3.1 25
11— **[Water]** 24
9— P.P.G.= 24 % 23
7— E.P.G.s= 8 g/ha 22
5— 21
3— Rainfall 20
1— 3mm 19
-1— To Date P.G.= 25 g/ha 18

30 mm water

13— 42
P.I.= 2.3 **[Nitrate-N]** 41
11— 40
9— P.P.G.= 18 % E.P.G.= 14 g/ha 39
7— 38
5— 37
3— Rainfall 36
1— 3mm 35
-1— To Date P.G.= 41 g/ha 34
33
32

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

N_2O-N Running Total [dashed line] (g/ha)

30 mm water

13— 304
P.I.= 2.6 302
11— 300
9— P.P.G.= 20 % 298
7— E.P.G.= 12 g/ha 296
5— **[Nitrate-N]+ [Glucose-C]** 294
3— Rainfall 292
1— 3mm 290
-1—
15 16 17 18 19 20 21 22

Time (days)

V
E
G
A
S

Event # 3

Figure I.4.C. Vegas N_2O emissions for the four treatments in Event #3. Other features are the same as for Figure I.4.A.

55

Figure I.5.A. Flaminia N_2O emissions for the four treatments in Event #1. Other features are the same as for Figure I.4.A.

56

Figure I.5.B. Flaminia N_2O emissions for first four treatments in Event #2. See text and Table I.3 for definitions of treatments. Other features are the same as for Figure I.4.A.

57

10 mm water + dissolved Litter Organic-C

P.I.= 10.3

E.P.G.= 121 g/ha

P.P.G.= 72 %   [LitterExctract-C]

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

1,750
1,300
850
400
-50

130
120
110
100
90
80
70
60
50
40
30

10 mm water + dissolved 50 kg/ha NaNO3-N
+ dissolved Litter Organic-C

P.I.= 7.3

E.P.G.= 296 g/ha

[Nitrate-N]+[LitterExctract-C]

P.P.G.= 50 %

1,750
1,300
850
400
-50

300
250
200
150
100
50
0

N_2O-N Running Total [dashed line] (g/ha)

10 mm water + dissolved 50 kg/ha Urea-N
+ dissolved Litter Organic-C

P.I.= 9.8

E.P.G.= 207 g/ha

[Urea-N]+ [LitterExctract-C]

P.P.G.= 68 %

1,750
1,300
850
400
-50

220
200
180
160
140
120
100
80
60

0   1   2   3   4   5   6   7

Time (days)

FLAMINIA

Event # 2

Figure I.5.C. Flaminia N_2O emissions for last three treatments in Event #2. See text and Table I.3 for definitions of treatments. Other features are the same as for Figure I.4.A.

58

PART II

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)

60

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

62

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

63

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

64

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

66

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

67

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

68

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

69

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

70

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 $\cdot$ 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^{TM}), 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^{TM}). The standards used in the analysis were nitrous oxide in dinitrogen gas mixtures, at 338, 513 and 971 ppbv (Scott Specialty Gases), with the

71

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.

<u>Savanna Grassland (Cl)</u> . 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

72

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

73

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 · ha^{-1} (·24h^{-1}) fell BDL (Figure II.3.A; Table II.6).

74

For Event #2, 150 days after fire, there was a small background emission of 1 g N_2O-N $\cdot$ ha^{-1} $\cdot$ d^{-1} before the simulated rainfall (Figure II.3.A). After 20 mm water addition most other flux measurements fell BDL. The soil N_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 $\cdot$ ha^{-1} $\cdot$ d^{-1} in a one day episodic flux fell BDL (Table II.6).

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

In conclusion, during the wet season the Cs savanna showed very weak or undetectable N_2O fluxes to the atmosphere, be it quasi-climax, 18

75

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

76

emitted/consumed fell BDL or slightly above, with 0.6 g N_2O-$N \cdot ha^{-1}$ 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_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

77

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

78

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.

79

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 $\cdot$ ha^{-1} in 96 h (0.45 g N_2O-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

80

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-N $\cdot$ ha^{-1} in 96 h (1.1 g N_2O-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

81

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 $\cdot$ ha^{-1} in 96 h (0.45 g N_2O-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_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

82

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 $\cdot$ ha^{-1} in 96 h (2.3 g N_2O-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)

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)$_2$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

83

emission of 3.7 g N_2O-N $\cdot$ 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 $\cdot$ 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 $\cdot$ ha^{-1} $\cdot$ d^{-1}, and averaged of 12 g N_2O-N $\cdot$ ha^{-1} $\cdot$ 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 $\cdot$ ha^{-1} $\cdot$ 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-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 $\cdot$ 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_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

87

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.

89

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

90

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.

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)

92

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
C1– 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

95

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

97

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

N₂O-N Flux from Soil (g/ha.day)

4.75
3.5
2.25
1
-0.25
-1.5

Event #2
20 mm water

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

atm.

atm.

360
330
300
270
240
210
180

360
330
300
270
240
210
180

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.

101

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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.

103

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.

104

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_2O emissions for wooded savanna (Ct) site. Other features are the same as for Figure II.3.A.

Savanna Woodland (flux) *Cd*

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.

108

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

109

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

110

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.

111

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.

112

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.

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_2O 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 N₂O 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.

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126

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129

APPENDIX A

CORRECTIONS FOR GAS LEAKS IN THE SAMPLING SYRINGES

The body of the syringes used for sampling of gas, either for flux or for soil-gas-phase profile measurements, were made of nylon with butyl rubber O-ring seal on the working piston. Due to wear and scratching of the inner walls, mostly due to dust and other abrasive particles collecting there during field work, some diffusional leak of the samples stored in those syringes occurred in the Costa Rican study, from the time of sampling to the time of analysis. In order to correct the analyzed N_2O concentrations to the original sampled concentration values, the diffusional leaks had to be assessed. The procedure described below was utilized to correct for this problem.

A complete series of leak tests was conducted on every syringe used in the experiments. The passive leak test consisted of washing the syringes three times with the known standard (800 ppbv N_2O in Nitrogen) before filling with the same standard and closing shut the syringe stopcock valve. These were then left on the bench for approximately 48h, a span twice as long as the average residence time for the real experiment samples, and then analyzed against the same standard. A first order exponential decay constant (k) for each syringe was then computed from the amount of N_2O lost over the period.

131

The exponential diffusive leak function is

$$(C_1 - C_{atm}) = (C_0 \cdot e^{-kt} - C_{atm})$$

Where

      C_0 is the analyzed mixing ratio
      C_1 is the corrected mixing ratio
      k is the first order exponential decay constant
      t is the time between sampling (or filling in the leak tests) and
           analyzing
      C_{atm} is the background mixing ratio of N_2O in the troposphere in ppbv
           (310)

Once the time t was known, and k was determined for each syringe, C_1 could be determined. Because for most samples the N_2O mixing ratio differential to the atmosphere was high ($C_0 \gg C_{atm}$), the amount lost through diffusive leak ($C_1 - C_0$) in the time before analysis (t) wasn't high enough to lose the signal (when C_0 becomes = or indistinguishable from C_{atm}; see Figures A.1 through A.4).

After diffusional leak corrections were made it turned out to be relatively easy to flag data points where the original sampled signal had been lost. This may be attributed to the nature of the data which had to fall on a linear fit for flux samples and also because there were many repetitions in spatial proximity for the soil-gas-phase samples. The syringes also had diverse k values and were used randomly in the sampling. Those points were then considered outliers and were cast out. For the study of the savannas in Brazil, all syringes were retrofitted with a second O-ring and greased (see Methods, Part II) so that no detectable diffusive leak occurred.

132

Figure A.1. Scatterplot showing distribution of diffusional syringe leaks for Vegas samples collected for flux measurement.

Figure A.2. Scatterplot showing distribution of diffusional syringe leaks for Vegas soil-gas-phase samples.

134

Figure A.3. Scatterplot showing distribution of diffusional syringe leaks for Flaminia samples collected for flux measurement.

Figure A.4. Scatterplot showing distribution of diffusional syringe leaks for Flaminia soil-gas-phase samples.

136

APPENDIX B

FILE: THEDATA.WB1

CONTROL FU3 [no water added]   [no fertilizer ammendment]

Nominal Time	Real time days	NITRATE mg N/kg soil					AMMONIUM mg N/kg soil					GAS PROFILES ppbv					FLUX gN/ha.d	SOIL WATER TENSION mBars				
		2cm	5cm	10 cm	20cm	40cm	2cm	5cm	10 cm	20cm	40cm	2cm	5cm	10 cm	20cm	40cm		2 cm	5 cm	10 cm	20 cm	40 cm
0 h	0.0	16.68	44.14	4.06	2.11	0.45	6.98	17.45	1.13	1.06	0.20	371	375	401	423	468	2.10					
30 min	0.1																					
2 h	0.2																					
4 h	0.3																					
8 h	0.5																					
24 h	1.3	14.11	10.75	5.34	1.73	0.96	19.40	2.91	0.79	-0.26	0.45	340	421	405	512	573	5.70					
60 h	3.0	2.28	11.20	6.55	1.66	0.51	0.89	5.16	1.92	3.11	0.29	326	364	391	439	473	4.00					
144 h	5.9											322	343	358	395	442	-2.10					
2 - 0 h	8.9	25.51	36.68	3.14	0.94	0.85	27.70	5.65	1.56	1.36	0.37	324	339	349	372	398	-0.90					
2 - 30 min	9.1																					
2 - 2 h	9.1																					
2 - 4 h	9.2																					
2 - 8 h	9.4																					
2 - 24 h	10.2		5.24	5.65	1.79	0.96		5.93	3.62	0.68	0.17	314	342	360	382	400	0.30					
3 - 0 h	16.0		15.20	9.33	41.55	2.76		14.16	3.96	4.42	0.51	348	350	359	349	409	2.20					
3 - 30 min	16.1																					
3 - 2 h	16.2																					
3 - 4 h	16.2																					
3 - 8 h	16.4																					
3 - 24 h	17.1	0.48	26.47	7.07	4.10	19.25	0.41	26.02	1.66	2.68	12.93	323	331	344	374	387	0.60					
3 - 48 h	18.2											310	328	329	323	384	1.20					
3 - 72 h	19.2											329	320	335	339	346	8.30					
3 - 96 h	20.2											382	370	382	399	407	8.20					
3 - 144 h	22.1	21.79	12.44	4.63	1.73	0.14	29.66	2.39	1.60	0.33	0.05	359	368	391	351	423	1.40					

WATER FU1 [10/10/30mm water added 30 min before times 0.5/2-0.5/3-0.5 h.]   [no fertilizer ammendment]

Nominal Time	Real time days	NITRATE mg N/kg soil					AMMONIUM mg N/kg soil					GAS PROFILES ppbv					FLUX gN/ha.d	SOIL WATER TENSION mBars (average)				
		2cm	5cm	10 cm	20cm	40cm	2cm	5cm	10 cm	20cm	40cm	2cm	5cm	10 cm	20cm	40cm		2 cm	5 cm	10 cm	20 cm	40 cm
0 h	0.0	14.04	10.50	6.66	1.11	0.47	16.13	1.51	2.05	0.50	0.23	331	346	376	402	429	3.93	149	161	181	149	107
30 min	0.1	29.47	10.65	11.03	1.04	0.85	7.21	2.29	0.61	0.60	0.03	337	371	389	420	431	4.62	3	4	53	148	106
2 h	0.2	22.66	12.33	7.60	3.01	0.66	13.17	2.34	1.70	0.59	0.32	336	379	405	407	413	8.74	15	8	32	138	108
4 h	0.3	27.86	0.76	5.20	2.77	0.55	22.16	0.77	0.69	0.40	3.58	333	384	427	470	437	6.36	23	23	35	128	105
8 h	0.5	0.94	8.19	6.18	3.11	0.00	0.86	12.57	2.25	1.28	ERR	347	387	457	493	532	4.29	31	35	39	117	105
24 h	1.3	2.02	6.96	8.06	13.45	1.51	2.34	3.36	1.56	15.01	0.63	317	335	390	473	500	3.56	202	105	77	71	107
60 h	3.0	12.33	16.05	15.32	2.88	1.18	6.25	9.95	8.48	1.18	2.39	325	356	394	464	475	-2.78	188	227	180	129	104
144 h	5.9											332	347	349	416	429	5.80	604	711	403	209	105
2 - 0 h	8.9	17.78	11.84	9.62	11.78	1.28	11.70	4.04	2.27	3.39	0.77	320	336		370	391	0.72	322	590	437	216	96
2 - 30 min	9.1	9.41	11.39	6.61	3.98		3.74	6.20	7.66	1.60		363	368	363	396	400	9.70	13	15	364	244	95
2 - 2 h	9.1		7.71	4.98	13.23	1.63		3.17	1.44	5.99	-1.03	356	362	389	418	406	9.06	45	47	334	231	112
2 - 4 h	9.2	29.46	14.27	6.96	2.80		8.01	1.07	3.46	2.29		340	349	358	396	409	4.80	77	86	288	241	116
2 - 8 h	9.4	28.54	17.92	13.19	5.24		10.84	11.46	4.09	1.18		311	324	349	389	398	3.51	91	130	293	245	119
2 - 24 h	10.2	17.94	28.35	14.75	1.88		16.77	31.47	4.05	0.88		316	333	346	354	417	6.63	164	141	183	98	13
3 - 0 h	16.0	28.32	21.33	13.05	2.10	0.89	32.27	11.07	1.57	2.32	0.34	337	336	358	378	390	4.29	153	108	367	328	103
3 - 30 min	16.1	9.93	2.96	3.27	1.59		11.32	1.89	1.27	-0.09		356	382	388	423	379	6.86	7	6	245	161	93
3 - 2 h	16.2	12.39	11.96	6.84	1.59		10.03	6.10	3.46	1.38		384	421	491	313	379	11.82	14	14	6	14	74
3 - 4 h	16.2	28.42	9.98	5.23	1.86		7.39	6.79	1.93	1.93		359	506	592	520	456	5.49	37	34	19	19	71
3 - 8 h	16.4	14.22	16.04	3.84	0.93		26.49	6.75	0.27	-0.14		323	351	386	466	458	2.50	49	41	27	26	67
3 - 24 h	17.1	1.59	1.69	7.97	23.79		0.19	0.96	7.76	35.20		325	338	376	424	422	0.89	124	60	37	37	54
3 - 48 h	18.2											319	330	353	364	396	3.35	210	97	109	54	53
3 - 72 h	19.2											327	328	362	316	411	7.60	187	89	117	65	56
3 - 96 h	20.2											333	347	366	403	402	1.94	136	134	110	74	25
3 - 144 h	22.1	17.30	7.55	2.32	33.98	0.34	41.04	4.02	1.46	29.22	1.11	338	368	388	371	465	3.58	34	32	40	68	23

V E G A S

NITROGEN

10/10/30mm water added 30 min before   times 0.5/2-0.5/3-0.5 h | **dissolved fertilizer amendment: 50kg/ha Nitrogen equivalent (NaNO3)**

Nominal Time	Real time days	NITRATE mg N/kg soil					AMMONIUM mg N/kg soil					FLUX gN/ha.d	GAS PROFILES ppbv					SOIL WATER TENSION mBars (average)				
		2cm	5cm	10cm	20cm	40cm	2cm	5cm	10cm	20cm	40cm		2cm	5cm	10cm	20cm	40cm	2cm	5cm	10cm	20cm	40cm
0h	0.0	16.51	13.25	5.45	2.46	0.44	5.92	4.82	1.10	1.22	0.15	6.78	337	384	383	403	435	149	161	181	149	107
30 min	0.1	51.91	20.29	11.30	1.70	0.59	11.90	8.42	1.67	0.57	0.26	0.00	383	401	386	391	417	3	4	53	148	106
2 h	0.2	38.91	22.27	1.83	1.70	0.14	5.00	2.77	1.03	0.53	-0.61	15.38	432	483	446	445	428	15	8	32	138	108
4 h	0.3	57.76	51.95	7.81	2.36	0.36	30.87	16.69	1.25	1.56	0.30	17.43	401	460	477	536	444	23	23	35	128	105
8 h	0.5	50.24	52.87	9.60	2.46	0.75	28.33	14.10	5.98	1.71	0.59	12.73	383	427	466	447	467	31	35	39	117	105
24 h	1.3	50.31	53.71	10.08	11.67	9.32	20.04	23.33	2.03	13.80	7.04	8.72	326	365	490	541	682	202	105	77	71	107
60 h	3.0	44.30	41.36	1.01	2.09	0.32	26.61	7.87	0.67	1.86	1.65	3.17	332	359		449	520	188	227	180	129	104
144 h	5.9											3.22			364	383	416	604	711	403	209	105
2 - 0 h	8.9	43.21	21.03	10.64	4.53	0.11	29.10	5.96	3.94	3.06	0.54	4.69	307	330	347	383	393	322	590	437	216	96
2 - 30 min	9.1	3.55	27.95	12.61	3.71		-0.49	6.34	7.29	1.82		7.81	403	330	383	383	400	13	15	364	244	95
2 - 2 h	9.1	51.69	24.17	12.48	3.37		27.45	2.99	8.59	1.46		8.04	398	401		407	409	45	47	334	231	112
2 - 4 h	9.2	50.89	40.54	17.46	4.51		27.30	14.96	9.17	1.61		6.57	356	377	393	413	409	77	86	288	241	116
2 - 8 h	9.4	51.51	26.69	6.26	2.99		32.31	7.37	1.38	1.27		5.87	330	350	369	336	405	91	130	293	245	119
2 - 24 h	10.2	46.35	25.53	10.81	3.27		34.08	4.05	3.78	2.04		9.02	374	369	409	397	412	164	141	183	98	13
3 - 0 h	16.0	43.52	15.91	7.51	3.38	0.37	26.30	3.50	1.95	0.68	0.63	7.40	334	376	360	403	400	153	108	367	328	103
3 - 30 min	16.1	50.79	50.72	19.88	3.48		15.58	8.05	2.85	1.00		6.67	314	438	406	390	401	7	6	245	161	93
3 - 2 h	16.1	5.98	49.27	17.74	3.73		1.57	3.81	1.22	1.30		13.31	414	360	656	686	382	14	14	6	14	74
3 - 4 h	16.2	49.75	2.62	12.04	52.48		35.75	1.68	2.86	7.21		12.16	452	477	817	819	451	37	34	19	19	71
3 - 8 h	16.4	45.45	40.93	24.91	2.84		18.18	6.16	4.29	2.07		5.48	358	384	531	536	417	49	41	27	26	67
3 - 24 h	17.1	45.60	46.88	44.86	2.99		33.08	8.04	-0.03	0.50		17.28	304	372	391		459	124	60	37	37	54
3 - 48 h	18.2											0.35	326	347	392	404	425	210	97	109	54	53
3 - 72 h	19.2											4.21	337	401	401	411	442	187	89	117	65	56
3 - 96 h	20.2											6.26	333	339	382	378	391	136	134	110	74	25
3 - 144 h	22.1	48.64	50.10	14.45	3.71	0.69	40.62	10.96	1.26		0.93	4.18	359	376	349	474	456	34	32	40	68	23

C + N

10/10/30mm water added 30 min before   times 0.5/2-0.5/3-0.5 h | **dissolved fertilizer amendment: 250kg/ha Carbon equivalent (glucose) + 50kg/ha Nitrogen equivalent (NaNO3)**

Nominal Time	Real time days	NITRATE mg N/kg soil					AMMONIUM mg N/kg soil					FLUX gN/ha.d	GAS PROFILES ppbv					SOIL WATER TENSION mBars (average)				
		2cm	5cm	10cm	20cm	40cm	2cm	5cm	10cm	20cm	40cm		2cm	5cm	10cm	20cm	40cm	2cm	5cm	10cm	20cm	40cm
0h	0.0	30.97	15.21	7.07	1.26	0.57	21.34	7.55	1.48	0.80	0.19	10.62	470	405	428	443	471	149	161	181	149	107
30 min	0.1	41.79	24.22	17.25	1.68		4.65	4.70	1.21	2.04		67.32	1302	1231	731	432	419	3	4	53	148	106
2 h	0.2	28.52	49.76	17.43		2.31	6.50	3.59	1.94		0.91	285.57	5418	4437	2874	863	477	15	8	32	138	108
4 h	0.3	50.99	35.93	23.68	3.08	0.29	6.24	1.59	2.45	1.60	0.09	605.83	10733	11180	9096	2828	1032	23	23	35	128	105
8 h	0.5											1500.86	10615	19105	19767	7720	3542	31	35	39	117	105
24 h	1.3	42.11	25.35	34.04	0.35	0.58	11.81	7.16	27.78	0.50	0.43	23.53	635	699	1153	1996	1908	202	105	77	71	107
60 h	3.0	47.67	16.00	4.64	1.70	19.14	7.73	1.63	3.53	0.96	5.24	3.52	413	423	497	552	614	188	227	180	129	104
144 h	5.9											1.80	399	381	433	434	476	604	711	403	209	105
2 - 0 h	8.9	36.32	28.69	19.96	1.36	0.06	6.33	2.37	2.33	1.12	1.29	2.95	354	355	361	387	402	322	590	437	216	96
2 - 30 min	9.1	50.23	22.55	5.20	1.13		5.14	4.38	0.92	0.49		40.18	611	582	425	387	405	13	15	364	244	95
2 - 2 h	9.1	48.73	21.09	4.38	0.88		3.06	1.59	0.87	1.15		28.09	533	489	982	458	419	45	47	334	231	112
2 - 4 h	9.2	44.72	30.27	11.90	2.09		8.19	1.94	1.24	1.10		14.42	416	435	433	435	418	77	86	288	241	116
2 - 8 h	9.4	49.45	15.77	1.53			14.67	2.64	0.59			7.06	366	397	413	463	505	91	130	293	245	119
2 - 24 h	10.2	46.43	23.08	2.71	1.21		4.85	2.34	0.98	0.36		4.90	362	379	409	445	495	164	141	183	98	13
3 - 0 h	16.0	1.61	4.91	2.60	1.61	0.59	12.39	1.66	0.67	0.63	0.41	3.69	345	360	363	410	413	153	108	367	328	103
3 - 30 min	16.1	38.04	10.04	7.27	1.19		20.96	1.84	0.82	0.82		3.38	494	463	982	467	409	7	6	245	161	93
3 - 2 h	16.1	47.70	46.90	8.26	2.91		21.37	6.32	1.85	0.56		19.85	566	584	641	509	434	14	14	6	14	74
3 - 4 h	16.2	48.66	28.45	7.12	2.64		13.53	3.94	1.66	0.77		15.08	490	471	672	679	515	37	34	19	19	71
3 - 8 h	16.4	44.16	35.77	5.25	2.38		12.51	2.89	0.75	1.93		6.17	402	404	545	635	577	49	41	27	26	67
3 - 24 h	17.1		6.78	6.80	2.57			4.35	1.08	4.33		8.52	366	370	433	473	512	124	60	37	37	54
3 - 48 h	18.2											4.02	337	338	382	444	441	210	97	109	54	53
3 - 72 h	19.2											4.46	358	360	391	423	456	187	89	117	65	56
3 - 96 h	20.2											4.51	386	367	406	442	458	136	134	110	74	25
3 - 144 h	22.1	48.08	47.40	37.75	3.71	0.93	8.47	1.64	3.78	1.08	0.23	6.10	352	366	458	507	479	34	32	40	68	23

139

140

FILE: THEDATA.WB1

WATER — FL1 — no fertilizer ammendment

FLAMINIA

Nominal Time	Real time days	NITRATE mg N/kg soil				AMMONIUM mg N/kg soil					GAS PROFILES ppbv					FLUX gN/ha.d	SOIL WATER TENSION mBars (average)				
		2cm	5cm	20cm	40cm	2cm	5cm	10 cm	20cm	40cm	2cm	5cm	10 cm	20cm	40cm		2 cm	5 cm	10 cm	20 cm	40 cm
0	0.0	15.81	8.85		1.14	44.90	2.51	8.56		5.21	682	947	1073	1526	1533	219.34	37.9	30.5	32.0	32.7	36.0
0.5	0.1	16.56	11.60			16.69	2.21	1.83			1194	1758	1806	2288	2005	570.89	8.3	6.7	3.0	1.2	13.3
2	0.2	18.58	9.65			15.22	3.23	2.65			1664	2683	3188	5607	3337	446.30	16.3	13.0	12.3	3.5	12.1
4	0.2	24.68	8.22			35.02	2.04	2.42			1208	1879	3053	4937	3184	399.83	22.9	24.2	23.0	11.8	9.8
8	0.4	11.38	4.96			44.39	3.06	2.47			747	1878	2269	3801	3051	142.84	32.5	31.1	27.0	16.6	16.5
24	1.1	17.03	15.69	1.97		29.14	2.21	2.64	1.09		1256	3626	4152	7312	7034	330.98	78.4	48.6	39.8	28.9	28.5
48	2.1	15.17	9.27	5.52		41.52	3.73	1.54	1.11		1154	3032	4007	7382	8414	138.11	150.6	66.7	52.7	38.1	36.5
72	3.2	49.01	46.03	12.67		8.50	2.17	3.95	1.11		1303	2583	2972	4802	4796	-205.10					
96	4.1	3.58	6.84	4.28		21.53	1.81	1.60	1.13		1253	3966	4636	6928	6832	250.17	19.4	20.8	19.5	7.9	8.1
144	6.1	5.06	8.62	3.31		36.97	2.18	2.01	0.87		791	2171	2605	5271	6207	373.14	57.5	36.7	33.3	20.8	25.6

NITROGEN — FL2 — dissolved fertilizer ammendment: 50Kg/ha Nitrogen equivalent (NaNO3).

FLAMINIA

Nominal Time	Real time days	NITRATE mg N/kg soil				AMMONIUM mg N/kg soil					GAS PROFILES ppbv					FLUX gN/ha.d	SOIL WATER TENSION mBars (average)				
		2cm	5cm	20cm	40cm	2cm	5cm	10 cm	20cm	40cm	2cm	5cm	10 cm	20cm	40cm		2 cm	5 cm	10 cm	20 cm	40 cm
0	0.0	6.74	2.97	0.52	0.05	8.66	4.95	2.04	0.80	0.63	344	459	519	667	764	1269.62	37.9	30.5	32.0	32.7	36.0
0.5	0.1	49.43	22.82			11.94	4.41	3.41			1688	1766	1546	1097	1629	622.47	8.3	6.7	3.0	1.2	13.3
2	0.2	46.95	30.56			11.75	4.45	2.26			477	2079	2384	3401	3982	871.80	16.3	13.0	12.3	3.5	12.1
4	0.2	40.66	10.71			14.74	2.85	2.38			458	750		1281	1492	3228.81	22.9	24.2	23.0	11.8	9.8
8	0.4	47.71	29.22			9.07	2.92	1.82			1421	1924	3274	7951	9984	463.53	32.5	31.1	27.0	16.6	16.5
24	1.1	33.63	46.50	23.18		3.33	7.24	34.46	1.28		441	702	949	1225	1296	4359.80	78.4	48.6	39.8	28.9	28.5
48	2.1	47.36	29.52	11.97		15.17	3.80	2.41	1.00		1345	1777	2125	8813	10168	372.81	150.6	66.7	52.7	38.1	36.5
72	3.2	11.41	16.05	0.80		46.65	3.06	1.49	0.93		1971	2399	2566	8331	9685	342.22					
96	4.1	11.92	46.96	12.91		26.43	4.49	3.75	1.80		3662	4560	7473	16896	14663	817.22	19.4	20.8	19.5	7.9	8.1
144	6.1	10.04	50.01	2.32		4.07	3.04	1.84	2.66		1465	3317	5416	6755	8522	653.10	57.5	36.7	33.3	20.8	25.6

CARBON FL3 — dissolved fertilizer ammendment: 250Kg/ha Carbon equivalent (glucose).

FLAMINIA

Nominal Time	Real time days	NITRATE mg N/kg soil				AMMONIUM mg N/kg soil					GAS PROFILES ppbv					FLUX gN/ha.d	SOIL WATER TENSION mBars (average)				
		2cm	5cm	20cm	40cm	2cm	5cm	10 cm	20cm	40cm	2cm	5cm	10 cm	20cm	40cm		2 cm	5 cm	10 cm	20 cm	40 cm
0	0.0	12.22	10.06	1.52	0.16	12.46	2.63	3.30	1.42	0.57	1263		1471	1891	2416	108.57	37.9	30.5	32.0	32.7	36.0
0.5	0.1	8.40	4.59			2.36	3.07	2.43			20767	14591	11381	3881	2470	13416.61	8.3	6.7	3.0	1.2	13.3
2	0.2	4.00	3.53			12.26	4.60	2.29			13021	49882	48782	31986	4728	30797.29	16.3	13.0	12.3	3.5	12.1
4	0.2	0.84	1.28			8.00	2.62	1.29			58895	69611	84593	57762	15545	15126.69	22.9	24.2	23.0	11.8	9.8
8	0.4	3.55	4.04			25.56	4.04	2.15			22404	32606	43100	35778	22174	6266.03	32.5	31.1	27.0	16.6	16.5
24	1.1	1.90	1.93	0.41		2.90	4.19	1.90	1.17		4644	11043	18642	26052	27608	0.00	78.4	48.6	39.8	28.9	28.5
48	2.1	5.92	9.37	8.69		5.74	3.53	1.42	0.98		1486	3382	6234	10728	14775	371.01	150.6	66.7	52.7	38.1	36.5
72	3.2	0.89	7.34	6.35		8.04	6.66	2.03	0.76		1590	3355	7035	9324	10360	209.67					
96	4.1	2.07	4.85	1.88		40.51	6.09	2.66	1.09		2380	5875	8886	10850	10747	238.43	19.4	20.8	19.5	7.9	8.1
144	6.1	17.17	4.89	4.00		0.63	2.45	1.33	0.83		1024	1438	3104	1817	10819	401.47	57.5	36.7	33.3	20.8	25.6

C + N FL4 — dissolved fertilizer ammendment: 250Kg/ha Carbon equivalent (glucose) + 50Kg/ha Nitrogen equivalent (NaNO3)

FLAMINIA

Nominal Time	Real time days	NITRATE mg N/kg soil				AMMONIUM mg N/kg soil					GAS PROFILES ppbv					FLUX gN/ha.d	SOIL WATER TENSION mBars (average)				
		2cm	5cm	20cm	40cm	2cm	5cm	10 cm	20cm	40cm	2cm	5cm	10 cm	20cm	40cm		2 cm	5 cm	10 cm	20 cm	40 cm
0	0.0	13.76	4.15	1.78	0.74	15.15	3.11	4.52	1.79	0.78		1106	2028	1181	3271	315.62	37.9	30.5	32.0	32.7	36.0
0.5	0.1	51.52	25.72			12.34	3.50	4.08			14349	13181	7241	4018	3557	3904.64	8.3	6.7	3.0	1.2	13.3
2	0.2	8.78	42.48			5.75	7.29	1.80			34579	37519	32491	15115	4619	19249.85	16.3	13.0	12.3	3.5	12.1
4	0.2	41.27	29.28			18.18	7.39	1.99				72914	77678	55373	15709	19282.06	22.9	24.2	23.0	11.8	9.8
8	0.4	49.63	24.91			10.31	3.02	2.74			42144	76565	105449	44894	30943	19380.46	32.5	31.1	27.0	16.6	16.5
24	1.1	47.83	29.75	7.13		12.81	2.83	2.62	1.45		4038	22601	40506	55705	89408	1534.64	78.4	48.6	39.8	28.9	28.5
48	2.1	47.92	24.97	1.17		7.85	5.77	1.86	1.50		32090	40808	15379	39952	39291	9676.62	150.6	66.7	52.7	38.1	36.5
72	3.2	52.76	52.15	1.98		25.94	2.84	2.34	1.01		13821	26164	35520	31296	22345	4545.42					
96	4.1	3.30	10.00	9.76		47.01	4.47	3.23	1.08		8093	28914	73779	69663	32367	2423.18	19.4	20.8	19.5	7.9	8.1
144	6.1	20.14	43.55	12.20		9.08	2.95	1.21	0.77		2134	6547	8064	22054	23879	1226.09	57.5	36.7	33.3	20.8	25.6