
Measurements of CO₂ exchange over a woodland savanna (Cerrado Sensu stricto) in southeast Brasil.

Humberto R. da Rocha¹, Helber C. Freitas¹, Rafael Rosolem¹, Robinson I.N. Juárez¹, Rafael N. Tannus¹, Marcos A. Ligo², Osvaldo M. R. Cabral², Maria A.F. Silva Dias¹

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1 Departamento de Ciências Atmosféricas, IAG/Universidade de São Paulo
2 EMBRAPA Meio Ambiente

Abstract

The technique of eddy correlation was used to measure the net ecosystem exchange over a woodland savanna (Cerrado Sensu stricto) site (Gleba Pé de Gigante) in southeast Brazil. The data set included measurements of climatological variables and soil respiration using static soil chambers. Data were collected during the period from 10 October 2000 to 30 March 2002. Measured soil respiration showed average values of 4.8 molCO₂ m⁻²s⁻¹ year round. Its seasonal differences varied from 2 to 8 molCO₂ m⁻²s⁻¹ (Q₁₀ = 4.9) during the dry (April to August) and wet season, respectively, and was concurrent with soil temperature and moisture variability. The net ecosystem CO₂ flux (NEE) variability is controlled by solar radiation, temperature and air humidity on diel course. Seasonally, soil moisture plays a strong role by inducing litterfall, reducing canopy photosynthetic activity and soil respiration. The net sign of NEE is negative (sink) in the wet season and early dry season, with rates around -25 kgC ha⁻¹day⁻¹, and values as low as 40 kgC ha⁻¹day⁻¹. NEE was positive (source) during most of the dry season, and changed into negative at the onset of rainy season. At critical times of soil moisture stress during the late dry season, the ecosystem experienced photosynthesis during daytime, although the net sign is positive (emission). Concurrent with dry season, the values appeared progressively positive from 5 to as much as 50 kgC ha⁻¹day⁻¹. The annual NEE sum appeared to be nearly in balance, or more exactly a small sink, equal to 0.1 0.3 tC ha⁻¹yr⁻¹, which we regard possibly as a realistic one, giving the constraining conditions imposed to the turbulent flux calculation, and favourable hypothesis of succession stages, climatic variability and CO₂ fertilization.

Key Words: Cerrado, savanna, photosynthesis, soil respiration, carbon sequestration, eddy correlation.

Resumo

A técnica de correlação dos vórtices turbulentos (eddy correlation) foi utilizada para se estimar a produtividade líquida do ecossistema (PLE) em uma área de Cerrado Sensu stricto, no sítio experimental da Gleba Pé de Gigante, no sudeste do Brasil. O conjunto de dados coletados incluiu também medidas de variáveis climatológicas e de respiração do solo com câmaras estáticas, no período de 10 de Outubro de 1999 a 30 de Março de 2002. A respiração do solo média anual foi de 4.8 molCO₂m⁻²s⁻¹, com diferenças sazonais que variaram entre 2 a 8 molCO₂ m⁻²s⁻¹ durante a estação seca (Abril a Agosto) e na estação chuvosa, respectivamente, por um padrão de sensível correlação com a temperatura (Q₁₀=4.9) e umidade do solo. Com base nos fluxos atmosféricos de CO₂, a PLE mostrou uma variabilidade no ciclo diurno grandemente controlada pela radiação solar, umidade e temperatura do ar. Na escala sazonal, a umidade do solo foi uma variável de alta correlação com a PLE, que aparentemente induziu a queda de folheto, redução da atividade fotossintética e da respiração do solo. O sinal da PLE foi negativo (sumidouro) na estação chuvosa e no início da estação seca, com taxas de -25 kgCha⁻¹dia⁻¹, e máximos de até 40 kgCha⁻¹dia⁻¹. Na estação seca o sinal foi positivo (emissão), o que foi revertido logo no início das chuvas. No fim da estação seca, em dias de grande estresse hídrico, ainda observou-se a resposta da fotossíntese na escala do ecossistema, mesmo tendo sido positiva a PLE. Paralelamente ao decorrer da estação seca, a PLE progressivamente aumentou de 5 até 50 kgCha⁻¹dia⁻¹. A soma anual da PLE mostrou-se aproximadamente balanceada, tendo sido no entanto, sob um viés de maior precisão, um pequeno mas significativo sumidouro de 0.1 0.3 tCha⁻¹ano⁻¹. Consideramos a hipótese de um pequeno sumidouro como possivelmente realista, dadas às restritivas correções impostas no cálculo dos fluxos turbulentos, e algumas hipóteses favoráveis de sucessão de estágios do Cerrado, fertilização de CO₂ atmosférico e variabilidade climática.

Palavras-chave: Palavras chave: Cerrado, savana, fotossíntese, respiração, sequestro de carbono, correlação dos vórtices turbulentos.

1. Introduction

The Cerrado is the largest savanna region in South America. Originally covering about 2×10^6 km² in Brasil, including the central region and parts of southeast, it has been reduced to only 20% at present (Mittermeier *et al.* 2000).

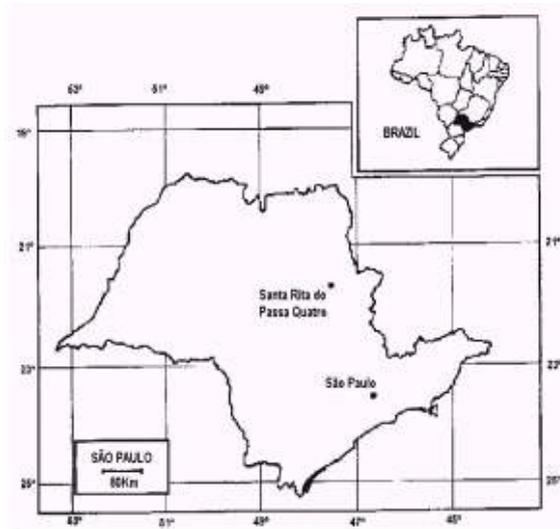
Several experimental studies have addressed the carbon exchange using automatic monitoring in the Amazon rain forests as part of the LBA Project (LBA 1996; Grace *et al.* 1996, Malhi *et al.* 1998, Goulden *et al.* 2002, Miller *et al.* 2002, Rocha *et al.* 2002). Pioneer studies in Brazilian savanna were reported by Miranda *et al.* (1997) in a Cerrado *Sensu stricto* in the central region, and by Vourlitis *et al.* (2001) in a Cerradão vegetation at the ecotone between tropical savanna and rain forest in Central Brasil. Related investigations in South America about water cycle and carbon stocks in tropical savanna were developed in Venezuela (San Jose *et al.* 2001; Szarzynsky and Anhuf *et al.* 1999).

In central Brazil the savanna is considered as the most threatened biome on the continent given the rapid expansion of agricultural frontiers (Silva and Bates 2002). The southeast region, originally covered with tropical evergreen forest along the coast (Mata Atlântica), tropical deciduous forests and savanna (Ratter 1992; Eiten 1972), is today dominated mostly by pasture, sugar cane and other crops (Rocha *et al.* 2000). Only a few and small fragments of Cerrado vegetation are conserved in the southeast.

In October 2000 we established a micrometeorological field station to make continuous observations of the local climate and the fluxes of heat, water and CO₂ between the atmosphere and a Cerrado *Sensu stricto*, located at the largest fragment remaining in the southeast (Santa Rita do Passa Quatro city, SP). In this paper we focus on the diel and seasonal patterns of CO₂ exchange (soil respiration and net ecosystem exchange), microclimate and soil moisture observed between 2000 and 2001.

2. Site and methods

The study was developed in the Vassununga state park, owned by the Instituto Florestal / São Paulo state, and located at Santa Rita do Passa Quatro city, SP, Brasil (Fig. 1a). The experimental site was placed at a reserve's part Gleba Pé de Gigante, a contiguous 1060 ha area of savanna vegetation (47°34' - 47°41' W, 21°36' - 21°44' S). Batalha (1997) reports coexistence of a few savanna physiognomies within the Gleba Pé de Gigante: (i) Cerradão (11%) 10 m tall trees, nearly closed canopies, dense litter; (ii) Cerrado *Sensu stricto* (79%) closed scrub and small (5m tall) trees, sparse taller trees (7-10 m tall), dense herbaceous story; (iii) Campo cerrado (8%) - open scrubland, sparse 7-10 m tall trees, dense herbaceous story; (iv) others Campo sujo and seasonal forest (2%). The prevailing soil type is quartz sand. The altitude within the reserve varies between 660 and 730 m.



(A)



(B)

Figure 1. (a) Geographical position of the experimental site in southeast Brasil; (b) photograph of micrometeorological tower at the Gleba Pé de Gigante.

An instrumental platform including automatic measurements of soil and climate variables, and turbulent atmospheric fluxes based at a scaffolding tower (21 m height, Hi-Way Access Intl) was established at the northwest sector (21°37'9"S, 47°37'58"W) in October 2000 (Fig. 1b). A data logger (Campbell CR10X) sampled the weather station and soil data every 15 s and recorded the averages on a 10 min basis. A full list of variables monitored at the site is presented in Table 1. The data discussed in this paper includes part of Table 1 and was collected from 10 October 2000 to 10 February 2002.

Variable (description)	Units	Sensor / Device
Air temperature	°C	Psychrometer CSI HMP45C
Air humidity	gkg ⁻¹	Psychrometer CSI HMP45C
Precipitation	mm	Texas 500
Wind direction	degrees	RM Young
Wind speed	ms ⁻¹	RM Young
Global solar radiation	W m ⁻²	LiCor 200X
PAR radiation	W m ⁻²	Licor Quantum
Net radiation	W m ⁻²	REBS
Soil moisture	m ³ m ⁻³	FDR CS615
Soil temperature	°C	CSI T108
Soil CO ₂ efflux	kgCO ₂ m ⁻² s ⁻¹	IRGA EGM-2 PPsystems
Latent heat flux	W m ⁻²	Eddy correlation
Sensible heat flux	W m ⁻²	Eddy correlation
Ground heat flux	W m ⁻²	REBS HFT3
Air total CO ₂ flux	kgCO ₂ m ⁻² s ⁻¹	Eddy correlation
Litterfall	kgCm ⁻²	Littertraps
Litter decomposition	kgCm ⁻²	Litterbags
Soil carbon	%	Soil samples
Streamflow	m ³ s ⁻¹	Water level gauge

Table 1: Collected variables at the observational site

An eddy correlation device measured the atmospheric turbulent fluxes of sensible heat, evapotranspiration, momentum flux and total CO₂ flux. It included a three-dimensional sonic anemometer (A1012R Gill Solent), an infra-red gas analyser for CO₂/H₂O (LiCOR 6262), an electromechanical system to control the pumped air from the sampler tube and record the 5 Hz frequency raw data. The eddy correlation method calculates the vertical flux of atmospheric carbon dioxide, F_c , taking the correlation between the deviations of the 30-minute average of the vertical wind speed (w') and the air CO₂ concentration (r_c'),

$$F_c = \overline{w' r_c'}, \quad (1)$$

a term usually referred to as the net ecosystem exchange (NEE), which theoretically accounts for the sum of gross primary productivity, plant respiration and soil respiration. The fluxes reported here were calculated using the 30-minute covariance following the detrending algorithms, coordinate rotation and frequency corrections described in Moncrieff *et al.* (1997). Soil respiration and soil temperature at 1 cm were measured using a portable static chamber (SRC-1, PP Systems, UK) sealed to the soil surface in closed circuit to a infra-red gas analyser (Parkinson, 1981), with an encapsulated thermistor placed near the chamber. Measurements with the chamber were carried out on a weekly basis over a set of seventeen collars fixed near the tower by April 2000.

2.1 Models

We have used numerical parameterizations of CO₂ flux for purposes of its calibration and validation at the field site. The algorithm employed is the SiB2 model (Sellers *et al.* 1996), which is a physical-mathematical concept of the soil-vegetation system for the exchanges of canopy radiative transfer, rainfall interception, soil hydraulic diffusion, and a stomatal conductance-photosynthesis function. The physiology is approached as of Collatz *et al.* (1991, 1992). Gross leaf assimilation rate is constrained by three factors: the assimilation rates defined by the photosynthetic enzyme system; the amount of PAR absorbed by leaf chlorophyll; and the capacity of the leaf to export or utilize the products of photosynthesis.

The SiB2 model was run in its off-line mode, *i.e.*, forced by *in situ* observations of meteorological 30-minute average variables, namely: global solar radiation, air temperature and humidity, wind speed and precipitation. Model validation requires optimisation methods and have been employed using eddy correlation data in tropical rain forests and pastureland (Rocha *et al.* 1996a,b). We used similar techniques to validate the model for the field site in order to fill gaps in the flux data.

3. Results and discussion

3.1 Climate

The climate is typically warm and wet in the summer, and mild and dry in the winter. In the period of observations a dry season was defined from May to September (Fig. 2a), an observation which approaches the regional climatology. The accumulated precipitation from 13 January 2001 to 12 January 2002 was 1322 mm (a period when the rainfall data had no gaps), which was a little below than the annual average (1478 mm) collected at the nearest station 20 km apart (DAEE, Santa Rita do Passa Quatro city). The wet season, during October to April, was marked by continuous days of precipitation, and showed a few cases of observations larger than 40 mm day⁻¹. We note two days with precipitation around 30 mm day⁻¹ in June, during the early dry season. It is not anomalous to observe sparse rainfall during the dry season, given the climatological precipitation in May, June, July and August are 43, 33, 20 and 21 mm, respectively.

Incoming solar radiation varied seasonally as the consequence of a maximum top of atmosphere irradiance in 22 December and a minimum in 22 June. The data appeared to be enveloped within the range between 30 (summer) to 18 (winter) MJm⁻²day⁻¹. Values as low as 4 MJm⁻²day⁻¹ were noticed in overcast days (Fig. 2b). The amplitude of canopy top air temperature varied with the solar radiation, from 5 to 35 °C year round (Fig. 2c). The penetration of (southerly) cold fronts is one of the most important regional controls of precipitation. It happens every 3 to 10 days, and is more frequent during the winter. These phenomena control the temperature remarkably

dropping the daily minimum during the winter as much as 10 °C (Fig. 2c). During the wet season, however, the effect of cold fronts, as well as generally the existence of rainy wet days, appears to drop the daily maximum temperature (which was observed to be roughly about 3 to 6 °C on the day-to-day variability). The presence of a semi-permanent large scale high pressure system over the region is typical during the autumn and wintertime, which is also suggested in Fig. 2d. Such a pattern is broken by the beginning wet season, as noticed by the onset of precipitation (Fig. 2a) and the seasonal surface air pressure changes occurred by middle September (Fig. 2d). The year round amplitude of air pressure variation was about 15 hPa. The turning point in the dynamics of large scale air masses at the dry to wet season transition has also an effect in the measured top canopy wind speed. The daily average wind was around 3 ms⁻¹ during most of the wet season and early dry season (Fig. 3a). During July to October, as precluded in the season transition, it increased by as much as 5 ms⁻¹ during several days. The prevailing surface winds are from the east, which result from the northern branch of the semi-permanent high pressure in the south Atlantic Ocean (Fig. 4). A small component is noted from the north-west direction at daytime, which is more typical at the proximity of precipitation systems, as convective clouds or cold fronts. At night it is noted the easterlies shift to south-east winds (Fig. 4b).

The reduced air temperature in the winter was

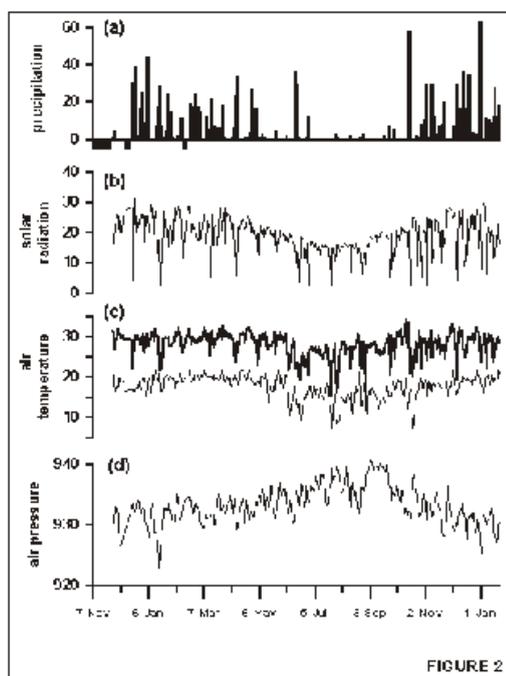


Figure 2. (a) Daily precipitation measured at 21 m, in mm day⁻¹; (b) Daily mean solar radiation at 21 m, in MJm⁻²day⁻¹; (c) Maximum (upper thick line) and minimum (lower thin line) daily air temperatures at 21 m, in °C; (d) Daily mean atmospheric pressure at 21 m height (in hPa). Data are shown for the period 15 Nov 2000 to 15 Jan 2002.

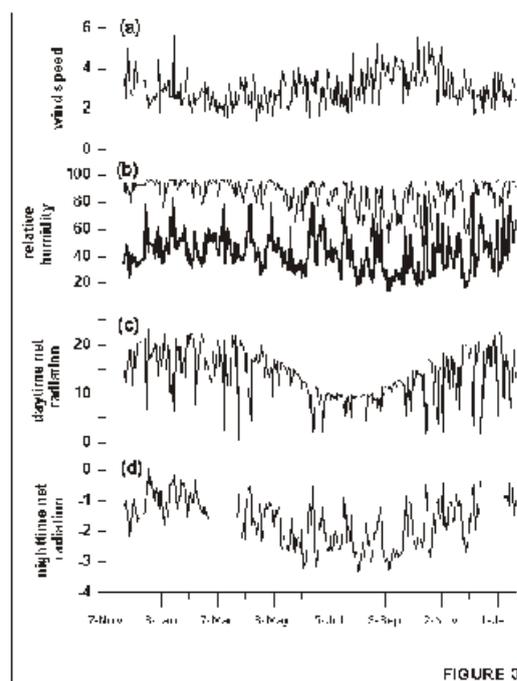


Figure 3. (a) Daily mean wind speed measured at 21 m, in ms⁻¹; (b) Daily maximum (upper thin line) and minimum (lower thick line) relative air humidity at 21 m, in %; (c) Daytime total net radiation at 21 m, in MJm⁻²day⁻¹; (d) Nighttime total net radiation at 21 m, in MJm⁻²day⁻¹. Data are shown for the period 15 Nov 2000 to 15 Jan 2002.

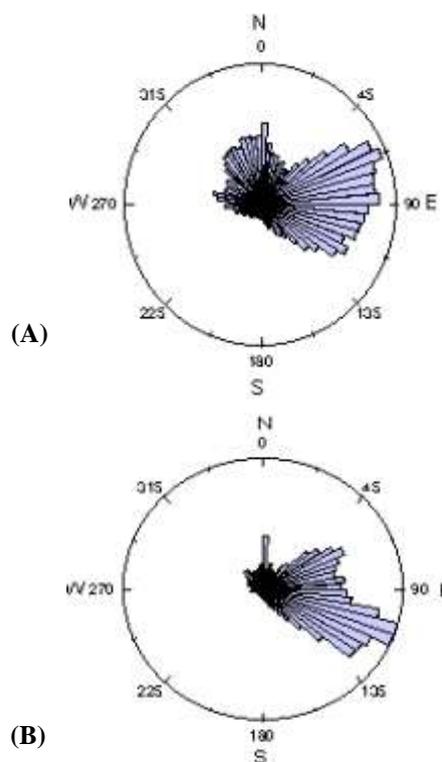


Figure 4. Prevailing wind direction (in degrees) during (a) daytime and (b) nighttime period, based on 30-minute average values measured at 21 m.

concurrent with reduced air humidity. Maximum daily relative humidity measured at top canopy varied from 100% (usually at night) in the wet season to about 60% in the dry season (Fig. 3b). As well, the minimum relative humidity varied with maxima daily temperature, from 50% to 15% year round.

Net radiation is the energy available to drive the air, soil and biomass heating, the water evaporation and the biophysical processes of transpiration and photosynthesis. Its seasonal course was well correlated with the solar radiation, as expected. The total daytime net radiation varied from 10 (in the winter) to 22 (in the summer) $\text{MJm}^{-2}\text{day}^{-1}$, as suggests the envelope of Fig. 3c. Clear nights have usually a larger loss of thermal infra-red energy thus reducing the net radiation and dropping the minimum air temperature. The nighttime net radiation is typically negative and during winter was markedly much lower ($-3 \text{ MJm}^{-2}\text{day}^{-1}$) than in the wet season ($1 \text{ MJm}^{-2}\text{day}^{-1}$), as shown in Fig. 3d.

3.2 Seasonal and diel courses

The variation of soil moisture in time is the balance between the inputs of precipitation and the losses of evapotranspiration and drainage. In the transition 2000/2001 wet season, the near surface (30 cm) soil moisture recharge was observed by early December. At the deeper levels (2.5 m) however, it lagged behind by roughly a month later. In the 2001/2002 wet season, differently, the recharge appeared earlier in time, as the onset of the wet season was markedly earlier.

On the seasonal basis, a marked control of soil moisture in the temporal evolution of the average 30-minute CO_2 fluxes is suggested in Fig. 5. Peak daytime uptake varied mostly between 15 and $30 \text{ molCO}_2 \text{ m}^{-2}\text{s}^{-1}$ in the wet season, whereas nighttime emission ranged typically between 0 and $15 \text{ molCO}_2 \text{ m}^{-2}\text{s}^{-1}$ (Fig. 5c). A broad reduction in the daily amplitude concurred with the developing dry season. By September the fluxes showed a positive sign, that is, suggesting a net emission of CO_2 . Likewise, such smooth and continuous trend of decreasing uptake after May and towards the dry season, was similarly shown by the evapotranspiration. Maximum daytime latent heat flux varied from 200 to 600 Wm^{-2} in the wet season, while in the late dry season the peaks were as low as 100 Wm^{-2} (Fig. 5b). We note from visual observations during site visits that during the dry season the vegetation experienced the fall of leaves. Most, if not all of the trees, are deciduous and a dramatic reduction in leaf area index was observed. The herbaceous layer also experienced the drying of leaves.

The CO_2 flux diel course in the high wet season showed daytime uptake of about $22 \text{ molCO}_2 \text{ m}^{-2}\text{s}^{-1}$ on the days 10 and 11 April 2001 (Fig. 6). Whilst these days had absence of rainfall, the 10th was mostly clear and the 11th was partially cloudy during daytime, as noticed by the oscillations in the solar radiation march. The CO_2 flux was

closely related to the intensity of solar radiation and evapotranspiration (Fig. 6b). While the air specific humidity substantially decreased during daytime from 17 to 14 g kg^{-1} , the soil moisture depletion was also observed, noticeably in the shallow layers (30 cm), and with less evidence at the 2.5 m depth (Fig. 6a). The reduction in soil moisture is the response of water withdrawal by the root system. The decreasing air humidity is suggested to play a significant control in stomatal control and consequently in leaf carbon assimilation during these events. At night the fluxes were positive, with values of approximately $5 \text{ molCO}_2 \text{ m}^{-2}\text{s}^{-1}$.

At the end of dry season the diel course indicated

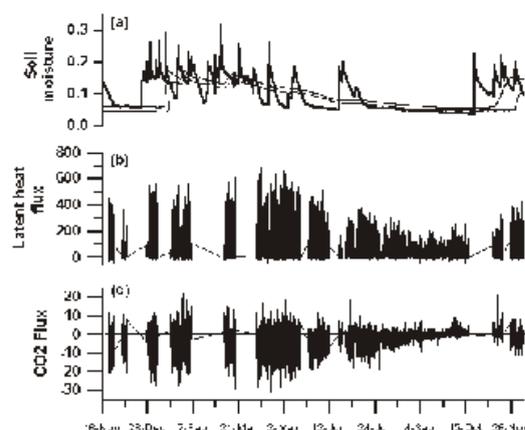


FIGURE 5

Figure 5. (A) Daily average volumetric soil moisture, in $\text{m}^3 \text{ m}^{-3}$, for a level at 30 cm depth (coarse line) and at 200 and 250 cm (thin lines); (b) 30-minute average values of latent heat flux, in Wm^{-2} ; (c) 30-minute average values of eddy CO_2 flux, in $\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$. Data are shown for the period 15 Nov 2000 to 10 Dec 2001.

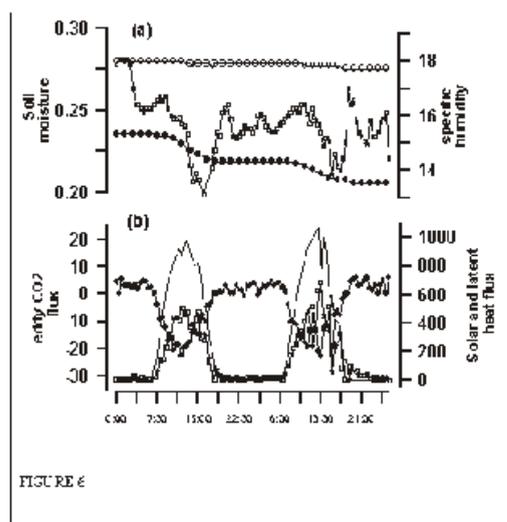


FIGURE 6

Figure 6. Diel course (Local Time) of 30-minute (a) (left axis) volumetric soil moisture, in $\text{m}^3 \text{ m}^{-3}$, for a level at 30 cm depth (black dots) and at 250 cm (open dots), and (right axis) air specific humidity, in g kg^{-1} (square dots); (b) (left axis) eddy CO_2 flux, in $\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ (black dots); (right axis) solar radiation (thin line) and latent heat flux (square dots), in Wm^{-2} . Data are shown for the days 10 and 11 April 2001.

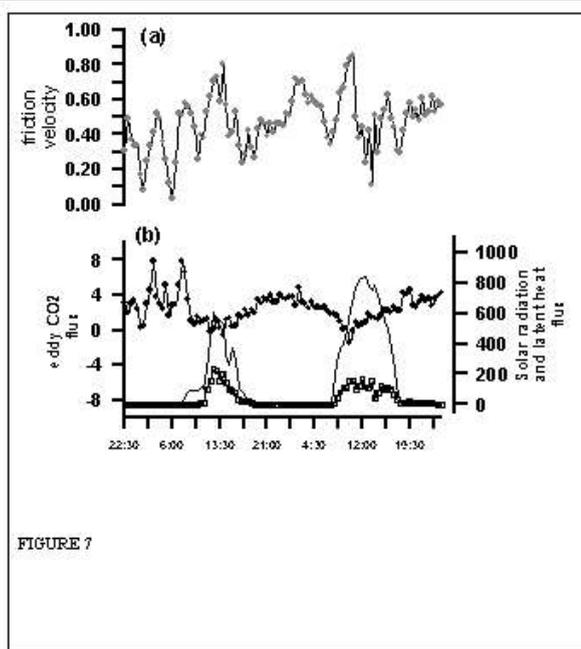


Figure 7. Diel course (Local Time) of 30-minute (a) (left axis) friction velocity measured at 21 m, in ms^{-1} (black dots); (b) (left axis) eddy CO_2 flux, in $\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ (black dots); (right axis) solar radiation (thin line) and latent heat flux (square dots), in Wm^{-2} . Data are shown for the days 8 and 9 October 2001.

positive (emission) fluxes. During the days 08 and 09 October 2001 the CO_2 fluxes ranged between -2 and 4 $\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ (Fig. 7b). These days showed the least ecosystem functionality in terms of CO_2 assimilation. These days showed the least ecosystem functionality in terms of CO_2 assimilation. It is noteworthy to mention that despite the prevailing positive fluxes, the CO_2 flux was noticeably more negative after sunrise, which is very presumably the response of photosynthesis. In other words, Fig. 7b suggests there are trees assimilating carbon despite the general aspect of dryness in the vegetation. The positive fluxes are simply the fact that soil and plant respiration rates overcome photosynthesis during those days. Radiation, temperature and air humidity were the main controllers of day-to-day variation in the top canopy measured CO_2 fluxes. Soil moisture exerts a strong control on the seasonal basis. During the dry season, the concurrent litterfall helps to increase (positively) the fluxes by reducing photosynthetic canopy activity and increasing decomposition.

At the night, between day 08 to 09, the fluxes increased smoothly up to values as high as 4 $\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ (Fig 7). In the previous night, however, it peaked following the pattern of the friction velocity (Fig. 7a). This correlation between the nighttime flux and the turbulent variable poses a weakness in this data to represent realistically the ecosystem CO_2 nighttime flux. The increasing friction velocity means more windy turbulence is generated at the canopy top. Consequently a well mixed layer between the ground and through the canopy air column is established. Given our measurements did not

include a CO_2 vertical profile in the instrumental platform, which could in theory account the storage in the canopy layer during these calm nights, the nighttime fluxes as shown are possibly underestimated.

3.3. Soil respiration

Independent from the eddy correlation measurements, the daily average soil respiration collected on a weekly basis varied between the minimum of 2 (in July 2001) to a maximum of 8 $\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ (in the high wet season), as shown in Fig. 8a. Soil respiration is the continuous loss of CO_2 by the respiration of roots, microbes, soil fauna and carbon oxidation. It depends largely on the ecosystem photosynthetic activity as well as leaf and litter decomposition. Therefore variables such as soil temperature and soil moisture ought to be major environmental controls. The average value was equal to 4.8 $\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ year round. Compared to measurements using similar methods (static portable chambers) in other tropical biomes, such average ranked roughly in an intermediate position between primary forests and active pasturelands (Table 2). The estimate of Meir et al. (1996) for similar vegetation was taken only in one month (April

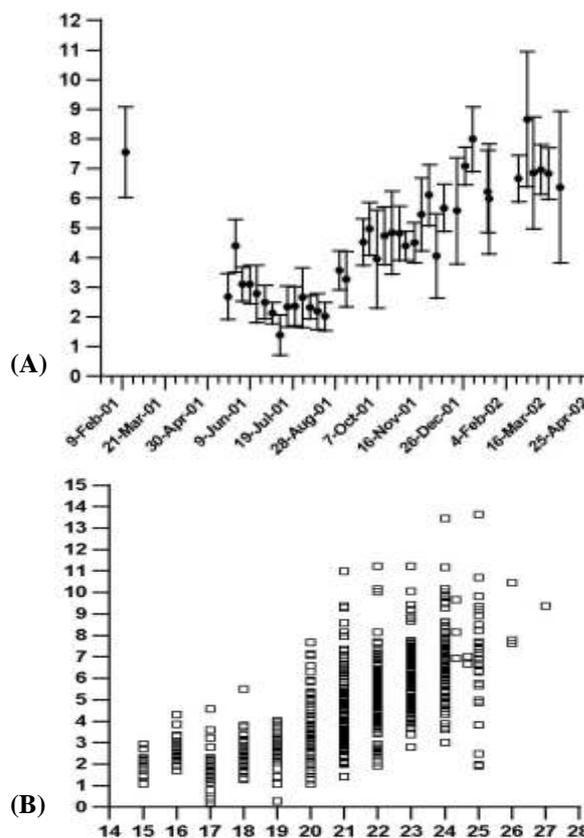


Figure 8. Soil respiration rates, in $\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$, (a) as daily averages and as a function of time with the respective daily standard deviation; (b) as instant values and as a function of instant soil temperature at 1 cm depth, in $^{\circ}\text{C}$.

1993), which is less representative of the yearly average. The increasing standard deviation as observed along the developing wet season (Fig. 8b) regards the increasing spatial variability prone to occur in those circumstances.

The comparison of soil respiration measurements with the correspondent soil temperature at 1 cm expressed a great deal of correlation (Fig. 8b). The data were used to fit an exponential relationship using the daily average values, which resulted in $R = \exp(0.1589 T_s - 1.8859)$, ($Q_{10} = 4.9$; $n = 40$; $R^2 = 0.755$), where R is the soil respiration in $\text{molCO}_2 \text{ m}^{-2} \text{ s}^{-1}$; T_s the soil temperature at 1 cm, in °C; R^2 is the correlation coefficient calculated over n points; and Q_{10} is the coefficient of the relative increase in soil respiration for a temperature increase of 10°C. The Q_{10} value calculated here is surprisingly large for a tropical ecosystem, which usually is between 2 to 4. The site is however near the tropics where the amplitude of soil temperatures are much larger than those observed near lower latitudes, for example in the Amazon. We do not know of other published values for comparison.

Forest	Secondary forest	Cerrado Sensu stricto	Active pasture	Degraded pasture	Site	Source
5.5-6.7	-	-	3.2-5.3	2.5-3.2	Paragominas	Trumbore et al. (1995)
5.5	-	-	-	-	Ji-Paraná	Meir et al (1996)
-	-	3.0	-	-	Brasília	Meir et al (1996)
5.2	4.7	-	3.9	2.6	Paragominas	Davidson et al (2000)
-	-	4.8 ± 2.2	-	-	Santa Rita Passa Quatro	(this study)

Table 2: Average soil respiration estimated in this work and in other similar works for Amazonian ecosystems (in $\text{molCO}_2 \text{ m}^{-2} \text{ s}^{-1}$).

3.4. Daily and annual sums

Calculating the annual sum of the half hour CO_2 average fluxes provides a particular estimate of how much carbon is possibly being emitted to the atmosphere (ecosystem is a source) or assimilated by the surface (ecosystem is a sink). Interannual variability can change the estimated amount, and even its sign (positive or negative), giving the plausible natural changes of ecosystem's recruitment and mortality rates, as well as variations in climate.

The raw data set as presented in Fig. 5 may not be sufficient to achieve a realistic annual sum estimate, for several reasons. A first one refers to missing flux intervals in the yearly record. A second one would be the lack of the CO_2 storage term measurements in the canopy profile. This term is supposed to account, at least partially, on the effect of processes not detected by the instruments located at the top canopy when the surface layer is stable, which is prone to happen typically on calm nights. A third reason regards some evidence raised for the ecosystem CO_2 loss, also on calm nights, as shown by the reduced flux mainly in tall forest canopies. In other words, it apparently suggests the

use of the eddy flux corrected by the storage term may not estimate all ways of exchange between the biological processes and the atmosphere. An alternative to address such problem has been suggested by using the so called u_* (friction velocity) filter, which removes the biased data that causes flux underestimation on the accumulated time series (Goulden et al. 1996, Miller et al. 2002). The question might very likely be site specific, depending on local relief and canopy architecture, between others.

Besides the aforementioned uncertainties in the annual sum, there are others related to the calculation of the individual average fluxes. These are namely the instrumental design and operation, and the approach to calculate the mathematical covariances. It has been noticed that low frequency contributions to the flux may be missed when insufficient averaging times are used (Sakai et al. 2001; Finnigan et al. 2002). In this case, the use of periods longer than 30-minute may be a way to better estimate the fluxes. Also, the method of detrending to ensure stationarity is in the realm of discussions. Despite that, Miller et al. (2002) compared linear detrending and block average removal for a data set in the tropical forest, and did not find significant differences on the annual sum.

Filling the gaps of a time series for the purposes of annual sum is not a simple task. Using daily accumulations calculated on periods near the gaps can provide a first alternative, although it does not solve the problem of day-to-day variability. In the present study, a broad variation occurred on the CO_2 diel course as well as on the seasonal patterns, and substantial differences can occur on time scales within a week. Such approach may introduce biases even more significant than the several uncertainties already involved in the experimental methodology. We used a biophysical surface-atmosphere model to provide the estimated fluxes during the gaps (see 2.2), in parallel with the soil respiration model fitted with our observations at the site. Net ecosystem assimilation (gross photosynthesis minus plant and soil respiration) is calculated during daytime, and soil and plant respiration during nighttime. The model was calibrated to account for the entire range of seasonal variability and was thus validated for the specific site and year. Forcing the model with canopy top 30 min average climate variables provided an estimate of the fluxes on the same time scale used in gap-free days.

The treatment of calm nights was approached by checking the u_* threshold sensitivity on the nighttime eddy fluxes and its comparison to model calculations. In this comparison the model is concerned as the best estimate of the 'true' flux, as it was based on independent field measurements and validated for the site. The plot of the nocturnal eddy fluxes and the model fluxes, constrained by u_* between 0 and 0.1 ms^{-1} , cleared indicated the eddy fluxes underestimated the model (Fig. 9a). Sequentially, similar comparisons taking the u_* values constrained between 0.1 and 0.2 ms^{-1} (Fig. 9b), 0.2 and 0.3 ms^{-1} (Fig. 9c) and 0.3 and 0.4 ms^{-1} (Fig. 9d), showed there was an improving correlation between the fluxes concurrent with increasing u_* . The comparison appears to be most favourable in the

range of u_s between 0.4 and 0.5 ms^{-1} (Fig. 9e).

The amount of data involved at each comparison in Fig. 9 obviously reduces as the threshold increases. For instance, taking the threshold equal to 0.1, 0.2, 0.3, 0.4, 0.5 and 0.6 ms^{-1} , the removal percentage of the nocturnal eddy fluxes was 48, 64, 80, 90, 95 and 98%, respectively.

We calculated the annual sums replacing the nocturnal eddy flux during weakly mixed periods with values provided by the calibrated model. The replacement was made sequentially, taking different u_s threshold filters. For illustration, the simple accumulation of the raw data (no gap filling and no filter) resulted in an annual sum of 3.2 $\text{tC ha}^{-1}\text{yr}^{-1}$ (Fig. 10). The filters produced outstanding changes in the annual sums, as well as changed the curve

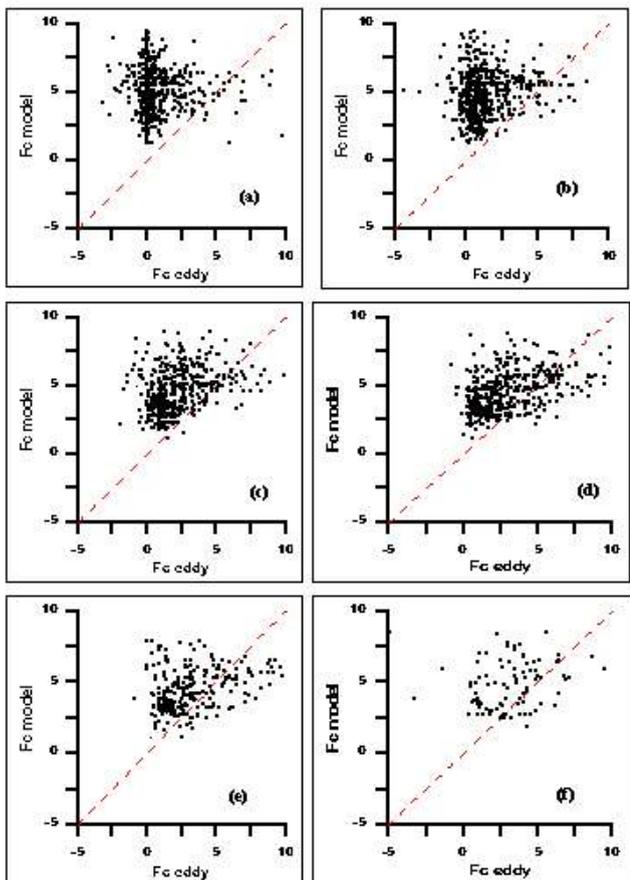


FIGURE 9

Figure 9. (y axis) Nighttime CO_2 flux modelled (SiB2 plant respiration and soil respiration based on exponential curve fitted from observations) against (abscissa) measured eddy CO_2 flux, compared for events constrained by a limited range of friction velocity u_s (in ms^{-1}) between (a) 0 to 0.1; (b) 0.1 to 0.2; (c) 0.2 to 0.3; (d) 0.3 to 0.4; (e) 0.4 to 0.5 and (f) 0.5 to 0.6. The 1:1 proportion is the dashed line.

shape of accumulations. At the 0.1 ms^{-1} threshold, the sum resulted in a negative flux of $-2.2 \text{ tC ha}^{-1}\text{yr}^{-1}$, which increased to about 1.2, -0.5, -0.1 and +0.2 $\text{tC ha}^{-1}\text{yr}^{-1}$ for thresholds increasing from 0.2 to 0.5 ms^{-1} , respectively. The variations between the annual sums that resulted with the use of increasing u_s filter tend to change in an inverse proportion, a result that Miller et al. (2002) also observed. This is partially explained by the fact that less and less nocturnal data are removed, consequently reducing the variations in the accumulations. It seems reasonable to think there should be a balance between disregarding bad data when the well mixed layer hypothesis does not work well, and keeping good data as much as possible. Neglecting good data can possibly increase the uncertainties in the annual sum. A point we search for is whether any filter can tell us where the optimal balance is.

The u_s threshold between 0.4 and 0.5 ms^{-1} was where the nocturnal eddy fluxes compared best the 'true' flux (Fig. 9e). At this stage, the annual sum showed roughly a limit where there was a small sink (at 0.4 ms^{-1}), or on the other hand, a small source (at 0.5 ms^{-1}), as shown in Fig. 10. While increasing the u_s threshold results in neglecting the eddy night-time flux, those should be kept as long as they do not mean actual underestimation. It has been said this filter can compensate the lack of nocturnal storage

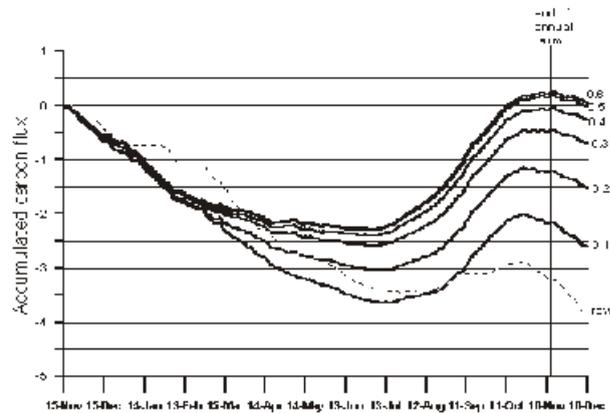


FIGURE 10

Figure 10. Annual sum of 30-minute net ecosystem exchange, in tC ha^{-1} , for the eddy raw data (thin line), and with gap-filled data constrained by u_s star filter with minimum threshold of 0.1 to 0.6 ms^{-1} (as shown at the right of thick lines).

measurement, which is supposed to correct the night-time emission under weak mixing. Nonetheless, an important issue is that the amount of stored CO_2 in the canopy is not changing with time, regardless the air column is well mixed or not. As well, the nocturnal storage can simply become negative for a point in u_s variation, what means the night-time turbulence is venting some of the stored CO_2 . In the latter case, the storage correction might reduce the emission indeed. Based on this, we think a defensible estimate for the annual would be to select the variation where the u_s threshold minimizes the night-time flux underestimation, that is, 0.4 and 0.5 ms^{-1} , and to take its

lower limit (0.4 ms^{-1}) as the most likely value that would less neglect good data. This would lead to an annual sum equal to $0.1 \text{ } 0.3 \text{ tC ha}^{-1}\text{yr}^{-1}$. The uncertainty was proposed by the variation between the annual sums calculated with the 0.5 and 0.4 ms^{-1} thresholds.

Using the threshold of 0.4 ms^{-1} we calculated a continuous time series of the net ecosystem exchange. In the wet season, the estimated uptake averaged varied around $-25 \text{ kgC ha}^{-1}\text{day}^{-1}$ with values as low as $40 \text{ kgC ha}^{-1}\text{day}^{-1}$ (Fig. 11). The changes occurring with the developing dry season are remarkable. In early May, negative fluxes of about $5 \text{ kgC ha}^{-1}\text{day}^{-1}$ are observed. They tend to increase progressively until middle August to values as large as $50 \text{ kgC ha}^{-1}\text{day}^{-1}$. The turning point between source and sink happens by early October. It appeared noteworthy that the transition sink to source took a little longer than the opposite. It is possibly explained by the rapid greening of the leaves during the onset of wet season, whereas the leaves fall at slower rates.

4. Conclusions

We have estimated the net ecosystem exchange over a Cerrado *Sensu stricto* in southeast Brazil (21° S) and emphasized the outstanding relationship of NEE functionality with the precipitation pattern: it appears to be a sink (source) well correlated with the wet (dry) season. Sink functionality may extend a little further in the early dry season. A similar pattern has been observed by Miranda *et al.* (1997) at a same biome in central Brazil (16° S), while Vourlitis *et al.* (2001), over a Cerradão site (11° S), have

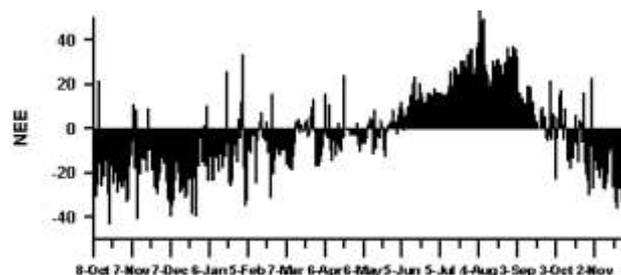


Figure 11. Daytime integrated values of net ecosystem exchange, in $\text{kgC ha}^{-1}\text{day}^{-1}$. Using gap-filled data constrained by the u . threshold of 0.4 ms^{-1} . Data are shown for the period 10 Oct 2000 to 10 Dec 2001.

particularly pointed out the dry and early wet season as the time of the year where net emission to the atmosphere prevail over assimilation. These three reports agree about the strong seasonality of NEE, mainly as compared to other measurements in Amazonian tropical forests (see introduction).

Our calculated annual sum over the Cerrado *Sensu stricto* suggests average NEE is nearly in balance, or more exactly a very small sink of 0.1 tC ha^{-1} . Similarly, Vourlitis *et al.* (2002) suggest a Cerradão site was also in balance after measurements between August 1999 and July 2001. It seems worthwhile to mention those authors report a very small difference between gross ecosystem exchange and ecosystem respiration, that is, 0.05 tC ha^{-1} , which ultimately means a weak although significant sink exists. In summary, these two independent studies over tropical savanna biomes show them to be apparently in balance, although small sinks were mathematically calculated.

That poses the question a small but significant carbon sink is realistic over the Cerrado, including all corrections involved in the eddy correlation approach to estimate annual NEE. We show arguments such hypothesis is viable, particularly for the Cerrado *Sensu stricto* site discussed in this paper. The Cerrado *Sensu stricto*, in general, can be viewed as an ecotone between the Campo Limpo and the Cerradão (Coutinho, 1978). Mostly, the classification of Cerrado biomes takes the canopy height as the indication to differ the several succession stages, as grass-scrub and scrub-tree stories might be common between several classes (Pivelo and Coutinho, 1996). The succession to stages with taller trees, and generally more biomass, should not be guaranteed. Limitations would be imposed by the soil type, that influence the nutrient cycle and available soil moisture - the latter is ultimately a consequence of precipitation regime and water available capacity. Fires would disturb the natural succession development on the short and medium term, although on the long term (decades to centuries) the Cerrado species are supposed to be adapted (Coutinho, 1978; Delitti *et al.* 2001). The mechanism of succession stages in the Cerrado biome has neither a complete agreement nor a comprehensive description in the literature, what makes the issue a challenging one.

The site Gleba Pé de Gigante might have been under some level of disturbance about at least 50 years ago, mostly used as natural pastures for cattle grazing, while fires and logging were not noticed on the very long term (Eng. Everton Ribeiro, personal communication). The soil type (mostly quartz sand very low water capacity) is not a favourable one for plants during dry spells, which consequently is a limitation for achieving higher levels of succession. However, the calculated sink is roughly 0.5 % of total biomass (based on estimates in the range of 17 to 25 tC ha^{-1} , as of Castro and Kauffman, 1998), which is viable to occur not only in terms of succession, but of climate oscillations on the interannual variability scale. Other controls exist and can respond for stimulating photosynthesis, as atmospheric CO_2 fertilization (see

Buckeridge and Aidar this issue). We are not aware neither of significant climatic anomalies (local temperature and rainfall) during the period of measurements, nor the response of natural species to CO₂ in environment conditions, mainly due the lack of information. It makes the issue of climate forcings and variability a key one to investigate in future analysis.

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