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# Landscape and climatic controls on spatial and temporal variation in soil $CO_2$ efflux in an Eastern Amazonian Rainforest, Caxiuanã, Brazil

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## Abstract

Quantification of temporal and spatial variation of soil $CO_2$ emissions is essential for an accurate interpretation of tower-based measurements of net ecosystem exchange. Here, we measured in the old-growth forest of Caxiuana, Eastern Amazonia soil $CO_2$ efflux and its environmental controls from two Oxisol sites with contrasting soil texture and at different landscape positions. Average $CO_2$ efflux was 21% higher for sand ($3.93 \pm 0.06$ μmol $CO_2$ $m^{-2}$ $s^{-1}$) than for the clay ($3.08 \pm 0.07$ μmol $CO_2$ $m^{-2}$ $s^{-1}$). No difference was detected for soil temperature between sites, while soil water content in sandy soil ($23.2 \pm 0.33$%) was much lower than the clay soil ($34.5 \pm 0.98$%), for the 2-year period. Soil $CO_2$ efflux did not differ between dry and wet season, but we detected a significant interaction between season and topographic position. The variation caused by topography was in the same order of magnitude as temporal variation. Mean contribution of the litter layer to the $CO_2$ efflux rates was 20% and varied from 25% during the wet season to close to 0% during the dry season. The relation between soil water content and soil $CO_2$ efflux showed an optimum for both soil textures but the shape and optimum of the curves were different. The results of our study illustrate that soil moisture is an important driver of temporal variations in soil $CO_2$ efflux in this old-growth forest. When extrapolating soil $CO_2$ efflux to larger areas, the significant influences of soil texture, litter, and the interaction of topographical position and time illustrate that it is necessary to include some of the complexity of landscapes.

*Keywords:* Amazon; Carbon cycle; $CO_2$; Litter; NEE; Soil respiration; Soil temperature; Soil water content; Spatial variation; Topography

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## 1. Introduction

In recent years, the recognition that old-growth forests of Amazonia play an important role in the global carbon cycle, has led to the establishment of several sites across the Amazon basin where net ecosystem exchange (NEE) of $CO_2$ is measured (Grace et al., 1995a; Malhi and Grace, 2000; Saleska et al., 2003). In the absence of fire, NEE is the net result of $CO_2$ uptake through photosynthesis and $CO_2$ losses through autotrophic and heterotrophic respiration. A major part of the respired $CO_2$ originates from the soil and quantifying the size and variation of this $CO_2$ source is critical for the correct interpretation of NEE measurements.

In contrast to tower-based NEE measurements, there are no standard methods to measure soil $CO_2$ efflux (or soil respiration) over larger areas; chambers, which normally cover only a fraction of a square meter are used. At the same time, soil $CO_2$ efflux is highly variable, both spatially and temporally (Hanson et al., 1993; Xu and Qi, 2001). As a result, estimates of the mean soil $CO_2$ efflux, even within homogeneous vegetation are uncertain. Spatial variability of soil $CO_2$ efflux, typically caused by variations in landscape, soils and vegetation (Xu and Qi, 2001; Schwendenmann et al., 2003) introduces a considerable level of uncertainty in modelling soil respiration at landscape and larger regional scales (Gough and Seiler, 2004). Temporal variability, mainly caused by climatic variables (Davidson et al., 2000), is a major source of error when estimating the cumulative annual soil $CO_2$ efflux (Janssens et al., 2000; Gough and Seiler, 2004).

Although the vast majority of soils in Amazonia have in common that they are heavily weathered, there is considerable spatial heterogeneity in soil texture both at local and regional scales (Sombroek, 1966; Jordan, 1985) and along topographic gradients (e.g., Silver et al., 2000). Furthermore, topographically induced microclimates and variations in soil water content

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can also cause spatial heterogeneity by affecting the ability to retain carbon, water, and nutrients (Running et al., 1987; Kang et al., 2000). Apart from soil texture and topography, the litter layer may also contribute to spatial and temporal variation of soil $CO_2$ efflux. Although litter input and turnover are frequently studied, the influence of the litter layer on temporal variation of soil $CO_2$ efflux has to our knowledge not been studied for tropical forests.

Because NEE measurements are done at high frequency and later integrated for longer time periods (hours to days), there is an increasing tendency to also collect soil $CO_2$ efflux at high frequency, with a limited amount of (automated) chambers (e.g., Goulden and Crill, 1997; Drewitt et al., 2002). While this approach leads to an excellent characterization of temporal variation, spatial variation can only be quantified between the few deployed chambers. As a result, soil $CO_2$ efflux is normally modelled using climatic parameters as input (most often soil temperature and sometimes soil moisture) thereby ignoring landscape variations in soil $CO_2$ efflux. This may lead to serious errors because the 'footprint' of tower-based measurements is normally large enough to cover considerable variation in landscape and soils (Grace et al., 1995b). An additional problem may be that soil temperature and soil moisture co-vary, even in tropical forest ecosystems, making it impossible to separate their effect on soil $CO_2$ efflux (Davidson et al., 2000; Schwendenmann et al., 2003).

Our goal was to quantify the spatial and seasonal variation in soil $CO_2$ efflux and its environmental controls in the old-growth forest of Caxiuana in the eastern Amazon. Using manually deployed flux chambers, we monitored soil $CO_2$ efflux from two Oxisol sites with contrasting soil texture over the course of 2 years. Furthermore we aimed to quantify the contribution of the litter layer to soil $CO_2$ efflux and to evaluate the effect of landscape position on $CO_2$ efflux. As the climate of the eastern Amazon is characterized by small fluctuations in temperature throughout the year, we expected that changes in soil water content would control the seasonal variation in soil $CO_2$ efflux.

## 2. Materials and methods

### 2.1. Study site

The experimental site was located in Caxiuanã National Forest, Pará, Brazil, (1°43′3.5″S, 51° 27′36″W). The forest is a lowland *terra firme* rainforest. Mean annual temperature is 25.7 °C. Mean annual rainfall is 2272 (±193) mm, with a dry season when only 555 (±116) mm of rainfall occurs on average (Fisher et al., 2006a). Months with more than 100 mm rainfall were assigned to the wet season (December–June), and the dry season consisted of the period of months with less than 100 mm rainfall (July–November).

Most soils (65% of the experimental site, Costa 2002) are yellow Oxisols (Brazilian classification Latossolo), but there are large differences in texture. Our study was on two Oxisols with contrasting soil texture: clay and sand (Table 1). Both soils have a broken laterite layer (0.3–0.4 m thick) at 3–4 m depth. The texture of the top 0.5 m of the sand is 75% sand and 25% clay + silt, while the topsoil of the clay had 31% sand and 69% clay + silt (Ruivo and Cunha, 2003). Mineralogy of both soils is mainly kaolinite in the clay fraction and quartz in the sand fraction (Ruivo and Cunha, 2003). The sites are located about 15 m above river level, and the water table has occasionally been observed at a depth of 10 m during the wet season (Fisher et al., 2006a). The forest structure does not vary much among soil types: 419 trees $ha^{-1}$ with a basal area of 25.1 $m^2$ $ha^{-1}$ and leaf area index (LAI) of 5.5 $m^2$ $m^{-2}$ on the clay soil and 434 trees $ha^{-1}$, a basal area of 23.9 $m^2$ $ha^{-1}$ and LAI of 5.2 $m^2$ $m^{-2}$ for the sand site (unpublished data D. Metcalfe). The height of the canopy is about 35 m, and the aboveground biomass is 200 $m^3$ $ha^{-1}$ (Lisboa et al., 1997). The forest presents considerable diversity, with species like *Dinizia excelsa* (angelim-vermelho), *Marmaroxylon racemosum* (angelim-rajado), *Couratari guianensis* (tauari), *Bucheniavia grandis* (tanimbuca), *Swartzia racemosa* (pitaíca), *Dipteryx odorata* (cumaru), among others (Almeida et al., 1993).

### 2.2. Design of experiment to measure effect of soil texture

Using a systematic design, 16 chambers were deployed on a 1 ha plot at the sand site, and 8 chambers on a 0.5 ha plot at the clay site. While eight chambers was enough to get a good estimate of soil $CO_2$ efflux, we used more chambers on the sand site because of an additional throughfall exclusion experiment which is not described here (Fisher et al., 2006a). In June 2001, PVC rings (0.296 m in diameter, 0.20 m tall) were inserted to a depth of 0.02 m into the soil. Once inserted, the rings were left in place throughout the period of measurements. Chambers were kept free of seedlings. Each of the two sites was sampled every 2 weeks from December 2001 to November 2002 and monthly from December 2002 to November 2003. It took 2

Table 1
Characterization of chemical and physical properties of the soil of our study area in Caxiuanã, Para, Brazil

| Texture/depth (cm) | Clay (%) | Silt (%) | Sand (%) | pH ($H_2O$) | ECEC ($cmol/dm^3$) | Total P (mg/kg) | Total C (g/kg) | Total N (g/kg) | SOC (g/kg) | Bulk density ($Mg/m^3$) |
|---|---|---|---|---|---|---|---|---|---|---|
| Sand | | | | | | | | | | |
| 0–10 | 14 | 10 | 77 | 4.5 | 3.1 | 3.4 | 9.6 | 0.40 | 9.5 | 1.49 |
| 10–100 | 23 | 7 | 70 | 4.4 | 2.2 | 1.2 | 4.3 | 0.38 | 4.8 | 1.53 |
| Clay | | | | | | | | | | |
| 0–10 | 38 | 23 | 40 | 3.9 | 5.7 | 4.4 | 13.7 | 0.57 | 15.1 | 1.20 |
| 10–100 | 56 | 20 | 24 | 4.2 | 2.4 | 2.0 | 6.7 | 0.68 | 5.9 | 1.22 |