Soil CO_2 exchange in seven pristine Amazonian rain forest sites in relation to soil temperature

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A B S T R A C T

We analysed soil respiration measurements made in seven distinctly different pristine rain forests in Central Amazon, ranging from stunted heath forest (Campina) to tall terra-firme rain forest. The differences in soil respiration fluxes between sites and their causes were investigated, as well as diurnal patterns and their dependency on temperature. Ensemble averages of hourly fluxes were calculated for both wet and dry seasons (as far as these were sampled). These values were processed using an analytical model estimating soil surface temperature from the temperature measured at two depths. The soil CO_2 efflux can be viewed as a proxy for forest productivity. The low productive Campina stunted heath forest site (on leached sandy soils and covered by scleromorphic vegetation) has the lowest respiration (<1.5 μmol CO_2 m^{-2} s^{-1}, dry period). Respiration increased in local patches of taller heath forest on finer textured soil to about 4 μmol CO_2 m^{-2} s^{-1}. In the Cuieiras lowland rain forest respiration changed along a toposequence. The lowest value of 2.5 μmol CO_2 m^{-2} s^{-1} was observed on the plateau (terra-firme rain forest), whereas a maximum of 6.0 μmol CO_2 m^{-2} s^{-1} was observed in the valley (Campinarana forest). Soil respiration decreased to about 4 μmol CO_2 m^{-2} s^{-1} close to the river (riparian forest) where soils remained close to saturation. To find the optimum correlation between soil temperature and respiration flux, relationships were derived between the amplitudes and phases of respiration and soil temperatures measured at different depths. Compared to the use of soil temperatures measured at 5 cm and 10 cm depth, the use of (modelled) soil surface temperatures strongly reduced the hysteresis between respiration and temperature, and improved the coefficient of determination (R^2) for the Cuieiras forest sites, whereas the Campina sites still showed time lags of several hours between respiration and soil temperature diurnal patterns. With respect to the surface temperature, Q_{10} ranged from 1.7 (bare soil, dry season) to 2.0–2.5 (Cuieiras slope and plateau sites, dry season) and 3.3–5.2 (ibidem, wet season) to 5.5–7.7 (Cuieiras Campinarana and valley forests, dry/wet season).

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1. Introduction

Soil respiration (soil CO_2 efflux or R_s) is the sum of autotrophic (living roots) and heterotrophic respiration (Metcalfe et al., 2011). Heterotrophic respiration, the microbial respiration of organic

matter, mycorrhizae and microbes subsisting on root exudates, is the final phase of the mineralization of organic substances and carbon turnover. It can be regarded as a direct proxy of the energy passing through biota (Kuzyakov and Gavrichkova, 2010). Knowledge of carbon turnover processes is important to understand the fate of the soil carbon pool (C). The soil carbon pool is estimated to globally be about three times the size of the atmospheric pool (760 Pg C) and 4.5 times the biotic pool (500–650 Pg C) (Gruber et al., 2004; Janzen, 2004; Lal, 2004). The global CO_2 emission by respiration, about 89 ± 12 Pg C y^{-1}, is the strongest terrestrial carbon source to the atmosphere (Raich et al., 2002) and increases

by $0.1 \, \mathrm{Pg \, C \, y^{-1}}$ in response to rising air temperatures (Raich et al., 2002; Bond-Lamberty and Thomson, 2010).

The contribution of the Amazon rain forest to the carbon cycle is of particular importance because of its huge primary production ($18 \, \mathrm{Pg \, C \, y^{-1}}$) (Malhi and Grace, 2000). The Amazon rain forest carbon cycle has been investigated with many different techniques, such as eddy-covariance measurements (Goulden et al., 2004; Araújo et al., 2010), soil chamber measurements (Meir et al., 1996; Sotta et al., 2004; Salimon et al., 2004; Zanchi et al., 2011), biomass assessments (Malhi et al., 2009a), hydrological carbon export studies (Richey et al., 2002; Waterloo et al., 2006) and remote sensing and airborne flux studies (Lloyd et al., 2007). However, upscaling the results remains difficult (Malhi et al., 2009a; Araújo et al., 2010; Davidson et al., 2012) because of the size of the Amazon Basin (6.6 million $\mathrm{km^2}$) and the heterogeneity of its vegetation, soil and micro-climate (Phillips et al., 1998; Zanchi et al., 2012).

There is a broad consensus about the need to validate models for ecosystems, especially for the tropical region due to climate anomalies and for ecosystems with significant total carbon stocks (Nobre et al., 1996; Waterloo et al., 2006; Malhi et al., 2009b). As only local measurements are available, one has to rely on modelling, employing relations observed for specific ecosystems. Thus, measurements are essential to get a reliable understanding of the processes driving soil respiration and help to further reduce uncertainties in the sensitivities of various models (Davidson et al., 2002; Zanchi et al., 2012). However, for the Amazonian as elsewhere, the relations of R_s with abiotic control variables are not yet sufficiently understood (Metcalfe et al., 2007) or even measured (Zanchi et al., 2012). In general, soil respiration has been shown to be controlled not only by soil temperature (T), but also by other environmental variables such as soil moisture, soil texture and composition, chemical properties and biomass of leaf litter and roots, tree size, as well as the activity of macro- and microfauna (Howard and Howard, 1993; Liski and Westma, 1997; Davidson et al., 1998; Irvine and Law, 2002; Bréchet et al., 2011). A major problem here is that root respiration and root exudate supply are driven by photosynthesis, which only has a remote connection to soil temperature (Tang et al., 2005; Baldocchi et al., 2006; Gaumont-Guay et al., 2008).

Though Amazonian studies have tried to determine how variations of R_s are controlled by biotic and abiotic variables (cf., Sotta et al., 2004; Salimon et al., 2004; Metcalfe et al., 2007; Bréchet et al., 2011; Zanchi et al., 2012), the relationships have appeared hard to disentangle. The main reason is that R_s measurements made over longer periods of time incorporating seasonal information are still scarce in the Amazon region (Zanchi et al., 2012).

An important question is: How does average respiration vary among forest types, soils and drainage status, and how can observed differences be explained? A consistent positive relationship between long-term soil respiration and different measures of plant production has been observed (Raich and Schlesinger, 1992; Metcalfe et al., 2011), which is expected as the release of carbon over long periods of time should balance the input (unless lateral transport and long-term changes in the carbon pool are important). Hence, understanding the site-dependency of respiration involves understanding of the site-specific carbon production.

For the temporal behaviour of respiration, soil temperature is one of the most important controlling physical variables. Although the temperature variation is relatively small in the Amazonian region its influence on respiration proves to be surprisingly large for some sites, as will be demonstrated by this study. In addition, observed differences in R_s between sites may be of interest for model development. The influence of T on R_s is usually conveyed in the Q_{10} factor (the factor by which the soil respiration rate changes when temperature increases by $10 \, ^{\circ}\mathrm{C}$) (Lloyd and Taylor, 1994; Reichstein et al., 2003). Use of the Q_{10}-factor to model soil R_s dependency on T can be complicated because ecosystem dynamics

can also cause time lags (hysteresis) (Baldocchi et al., 2006; Vargas and Allen, 2008; Phillips et al., 2012). These time lags (different phase between soil respiration and soil temperature patterns) have been documented in past studies (Pavelka et al., 2007; Graf et al., 2008; Subke and Bahn, 2010; Zanchi et al., 2012). The mechanisms that regulate these time lags might be driven by rhizosphere dynamics (Gaumont-Guay et al., 2008; Vargas and Allen, 2008), plant phenology and photosynthesis (Tang et al., 2005; Baldocchi et al., 2006; Vargas et al., 2010). A major difficulty for determining the key controlling factors (Kuzyakov and Gavrichkova, 2010) is the lack of accuracy in determining the seasonal variations in the biophysical lags (Högberg et al., 2001; Baldocchi et al., 2006; Graf et al., 2008; Vargas and Allen, 2008). To minimize the ecosystem hysteresis effect, some authors have used empirical relations from gas diffusion time lag measurements (Vargas and Allen, 2008; Pingintha et al., 2010) or analytical solutions (Gao et al., 2008; Graf et al., 2008; Sierra et al., 2011), Fourier, wavelet or stepwise analysis (Tang et al., 2005; Graf et al., 2008; Vargas et al., 2010) to analyse the dependencies between T and R_s data sets.

A methodological problem is that the observed phase shift between T and R_s temporal patterns depends on the soil temperature measurement depth (Graf et al., 2008; Vargas et al., 2010). Any arbitrary measurement depth of soil temperature yields a different apparent Q_{10} value for the soil temperature sensitivity of R_s (Phillips et al., 2012) because of phase shifts and the decrease in amplitude of the soil temperature with depth (Graf et al., 2008). However, most studies use a single and somewhat arbitrary temperature measurement depth, and the impact of changing soil temperatures patterns with soil depth is often not considered (Meir et al., 1996; Salimon et al., 2004; Sotta et al., 2004; Pinto-Junior et al., 2009). Gaumont-Guay et al. (2006) have suggested that the T–R_s curve with the lowest hysteresis would indicate the most appropriate temperature measurement. Pavelka et al. (2007) and Zanchi et al. (2012) also observed hysteresis in their measurements and recommended to find the maximum correlation by performing a cross-correlation analysis in which phase shifts between soil temperature time series at a certain depth and those of R_s were minimized. Although the use of cross-correlation analysis may be valid over short periods (no seasonality), application to annual time series incorporating seasonal variations in soil temperature and moisture would be problematic. This is because seasonal or inter-annual changes in soil thermal and CO_2 diffusivity could cause a shift in the effective depth of the CO_2 efflux activity in the soil profile (Graf et al., 2008; Subke and Bahn, 2010).

This study has two main aims. The first is to identify how soil respiration for seven different pristine tropical rain forest sites in Central Amazonia varies depending on site characteristics. Site averages were considered for wet and dry seasons separately. The second aim is to investigate the (site-dependent) short-term relationship between soil temperature and R_s, accounting for time lags. To achieve this, a simple analytical solution for the soil temperature change with depth is used, which can also be applied to other sites. This allowed investigation of at which depth the temperature will have the closest relation to soil respiration (such to define the optimum measurement depth). Unexplained results for the site-dependency of time-lags and Q_{10}-factors may serve to stimulate further investigations.

2. Site description

The study was conducted in the experimental areas *Reserva Biológica do Cuieiras – ZF2* ($2°36''32.67$ S, $60°12''33.48$ W, 40–110 m above sea level (a.s.l.)) and the *Reserva Biológica de Campina* ($2°35''30.26$ S, $60°01''48.79$ W, 93–101 m a.s.l.). Both reserves are