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Automated Monitoring of Soil Respiration: an Improved Automatic Chamber System

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Abstract

We designed, constructed and tested an automated chamber system for continuously monitoring soil respiration. Our objective was to design a system that would permit monitoring of CO_2 efflux rates over long time periods without altering microclimate inside the chamber. The measuring principle is based on the measurement of the increase in CO_2 concentration within an automated chamber in a fixed amount of time using a non linear regression method. The chamber operates by closing over the soil in response to a control signal and remains closed for a fixed amount of time. In this way, the chamber allows normal drying and wetting of the soil between measurements. We report results that show the reliability of soil CO_2 efflux measurements in comparison with Li-Cor 6400. The system holds great potential for long term continuous measurements campaigns in natural environments.

Key-words: soil respiration, continuous measurements, soil chambers.

1. Introduction

Soils store the largest C pool in terrestrial ecosystems (Schlesinger, 1997) and the fate of such pool depends ultimately on the balance between processes controlling soil C input (i.e. primary production, belowground C allocation, littering) and output (i.e. litter decomposition, soil CO_2 efflux, leaching of dissolved C). Soil Respiration (SR) is the outgoing flux of CO_2 from the soil to the atmosphere (μmol CO_2 m^{-2} s^{-1}); it is the sum of CO_2 fluxes coming from roots and rizosphere microbial respiration, the so called autotrophic respiration, plus the CO_2 produced by the soil biota decomposing soil organic carbon (heterotrophic respiration). There is a third component of SR referring to CO_2 coming from dynamic equilibrium of carbonates salts in soil solution. After photosynthesis, soil respiration is the second largest flux of carbon in most ecosystems. Thus, the current emphasis on ecosystem management for increased C sequestration requires an improvement in knowledge of soil respiration processes. The soil CO_2 fluxes can be measured by a variety of techniques but each technique can influence the apparent rates of respiration. Livingston and Hutchinson (1995) distinguished three different chamber techniques to measure soil respiration: closed static system, closed dynamic system and open dynamic system. In the first two types, the soil CO_2 efflux is estimated measuring the rate at which CO_2 increases within a chamber that has been placed on the soil for a certain amount of time. In the open dynamic system, the efflux is calculated as the difference between the CO_2 concentration at the inlet and the outlet of the chamber knowing the air mass flow going through. At the moment, no single method has been established as a standard (Pumpanen et al., 2004). Comprehensive reviews of the advantages and disadvantages of each type of sys-

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tem can be found in literature (Livingston and Hutchinson, 1995; Hutchinson and Livingston, 2002; Davidson et al., 2002; Kutsch at al., 2004). The primary problem for measurement of SR is the high spatial and temporal heterogeneity in the rates of soil CO_2 efflux (Xu and Qi, 2001). In fact, the soil CO_2 efflux can vary in response to soil temperature, soil water content and photosynthetic C input. In order to better understand the processes influencing CO_2 emissions from soils and to handle spatial and temporal heterogeneity, long term continuous measurements, based on automatic soil respiration systems, are required. These automatic systems are usually expensive and require continuous maintenance. Our objective was to develop, construct and test an automated closed dynamic system that will provide high temporal resolution measurements of soil CO_2 efflux over long period of time. In the present paper, we describe the system and we assess the reliability of CO_2 efflux measurements by comparison of this system with a conventional closed dynamic through flow chamber system (Li-Cor 6400 gas analyzer analysis console with Li6400-09 soil chamber) that was used as reference since it was shown to accurately measure CO_2 efflux rates (Pumpanen et al., 2004). Because soil CO_2 efflux is driven by diffusion and mass flow with the diffusion being controlled by CO_2 gradient and mass flow by pressure fluctuation at the soil surface, wind is one of the most important contributors to surface pressure fluctuations (Hutchinson and Mosier, 1981; Takle et al., 2004). In fact, under windy conditions, higher soil CO_2 efflux might be expected but few dataset in literature support this conclusion (Baldocchi and Meyers, 1991; Takle et al., 2004; Xu et al., 2006). In the present paper we also tested the influence of wind speed on the measured effluxes.

2. Materials and methods

2.1 The system

The system we developed can be classified as a closed dynamic system according to Livingston and Hutchinson (1995) and can manage up to twelve soil respiration chambers.

Each chamber consists of a steel collar (20 cm of diameter and 8 cm height) and an DC motor closing steel lid (it require 140 s to completely close), is placed on a steel collar inserted into the soil and the lid, when open, is in vertical position on North side of the collar to avoid shadowing (Fig. 1.A). Tightness of the lid closure is ensured by a neoprene cover on the inner surface of the lid and a rubber ring covering the top perimeter of the collar. The air is sampled from the centre of the lid and is returned by a manifold inside the collar. The connection between the chamber and the measuring system is realized with high density PVC tubing (10 m long, 4/6 mm inner/outer diameter). To avoid air pressure difference between inside and outside the chamber, a pressure vent was built according to the indication of Xu et al. (2006) and placed on the top of the chamber (Hutchinson and Livingston, 2001). The adopted vent design allows static pressure changes inside the chamber to follow whatever static pressure changes occur in the surrounding air outside the chamber both in calm and windy conditions while remaining insensitive to wind direction (Xu et al., 2006).

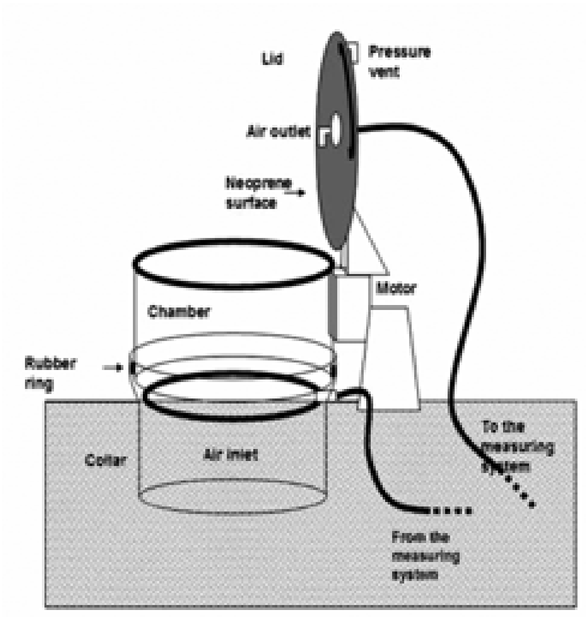

Figure 1.A. A drawing of the soil respiration chamber shown in the open position.

During the operation, air is circulated between the soil chamber to an infrared gas analyzer (IRGA, SBA-4, PP-Systems) at a constant flow rate (0.5 l min^{-1}). Air humidity, pressure and temperature are measured using the additional sensors provided by the PP-System with the IRGA and are acquired by parsing the digital output of the analyzer. The sequential sampling from the chamber is electronically controlled by a datalogger (CR1000 Campbell Sci. Inc. Lincoln Nebraska – USA) and a 16 channel AC/DC controller (SDM CD16-AC, Campbell Scientific) through the stimulation of couples of solenoids valves connected to the inlet and outlet of each chamber. When one pair of valves opens, the closure of the lid of the corresponding chamber is initiated by the software. The system is also equipped with a GSM base for remote control and data download.

The measuring principle is similar to the one used by the Li-Cor 8100 Automated Soil CO_2 Flux System (Li-Cor, Lincoln, NE, USA): the system uses the rate of increase of CO_2 within the chamber to estimate the rate at which CO_2 diffuses into free air outside the chamber. Atmospheric CO_2 is measured every second during lid closure and the final value (C_0, μmolCO_2 mol^{-1} of dry air) is recorded as the average of the last ten observations before lid closure (16 sec). After closure, CO_2 concentration (C, μmol-CO_2 mol^{-1} of dry air), water vapour mole fraction (W, mmol mol^{-1}), air temperature (T, °C) and air pressure (P, kPa) within the chamber are recorded using a RS-232 connection by the CR1000 every 1.6 second till chamber re-opening (Fig. 1.B).

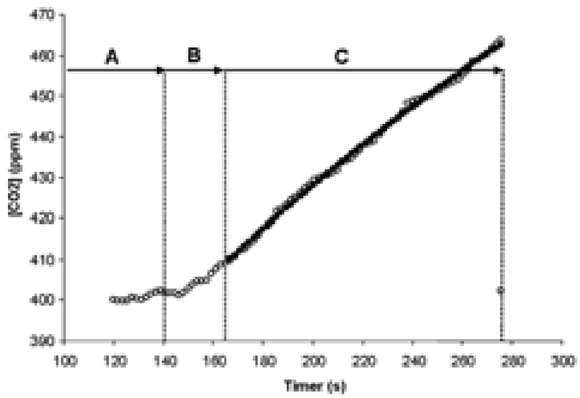

Figure 1.B. Principle of the measurement: chamber closure from 0 to 140 s and measure of the [CO_2] target as the average of the last 10 measures (A); mixing for 23 s (B); non-linear regression computation for 110 s (C); final efflux computation after 275 s. Open symbols are measured CO_2 concentrations; closed symbols are derived values from the computed non-linear regression.

To minimize the underestimation of the efflux due to the alteration of the diffusion gradient, we used a nonlinear curve fitting (Davidson et al., 2002; LI-COR, 2004): when a steady chamber mixing is established after lid closure (typically after 30-40 s) a non linear regression between [CO_2] and time is performed according to the equation (Fig. 1.B):

$$C(t) = C_x - (C_x - C_0)\, e^{-a\,(t - t_0)}$$

where $C(t)$ is the CO_2 concentration corrected by the water mole fraction, and C_x and a are estimated regression's parameters, C_0 is the initial concentration at chamber closure, C_x is the asymptote, and a is the parameter which defines the curvature: positive if $C_x > C_0$ or negative otherwise, t_0 represents the time when $C(t)$ is equal to C_0. The regression coefficients C_x, C_0 and a are calculated by the data logger using a non linear regression by a modified Gauss Newton iterative method. The initial rate of change in CO_2 (dC/dt) at C_0 and t_0 is computed using the equation:

$$dC/dt = a\,(C_x - C_0)\, e^{-a\,(t - t_0)}$$

Then, the Soil CO_2 efflux (μmol CO_2 m^{-2} s^{-1}) is computed using the following equation:

$$SR = \frac{V}{S} \cdot \frac{dC}{dt} \cdot \frac{P_0}{R \cdot (T_0 + 273.15)}$$

where P_0 and T_0 are the air pressure and air temperature measured as average of the last ten measure before lid closure; R is the universal gas constant (8.31 J mol^{-1} K^{-1}), V is system volume (cm^3) and S is chamber basal area (cm^2).

2.2 Field tests

We performed a comparison with the Li-Cor 6400 in order to assess the reliability of our system and a continuous long term monitoring of soil CO_2 efflux to study the influence of some environmental variables on the efflux. The site where both the tests were conducted is a corn field and is located in the Eastern part of Italy (46°00' N, 13°01' E). The soil has a bulk density of 1.1 g cm^{-3}, a stoniness of 21 % in weight and an organic carbon content of 22 tC / 1500 t of soil. The system was set up in the field at the beginning of September 2006. The comparison with the Li-Cor 6400 was performed two weeks after harvesting on 17th October 2006 between 8:00 to 16:00, while the continuous long term test of the system was performed at the same site from 17st October to 1st December 2006. During the comparison, the system was programmed to perform two cycles (two measurements on each chamber) every two hours; for the long term test, only one cycle was performed every 2 hours. One cycle lasted half an hour and then the second took place. The measurement with the Li-Cor 6400 was done after the chamber re-opening by placing the Li-Cor chamber on the soil within our system's chamber and performing three consecutive cycles. During the comparison, 40 measurements were taken (5 chambers x 2 cycle x 4 sessions).

2.3 Influence of wind

The pressure of a flowing fluid, P, is related to the density, ρ, and velocity, V, according to the equation:

$$P + 0.5\ \rho V^2 = \text{constant}$$

If we applied this equation to the vented chamber where the velocity of the air at the vent is the wind speed, V_1, and the velocity at the end of the tube connected to the vent inside the chamber is V_2 which is also that at the ground surface outside the chamber and equals zero, the pressure difference (P') is:

$$P' = P_2 = P_1 = 0.5 \cdot \sigma \cdot V_1^2$$

for $\rho = 1.2$ kg m^{-3} and with V_1 in m s^{-1}, we obtain

$$P' = 0.6 \cdot \sigma \cdot V_1^2$$

in *Pa*. We measured wind speed at 20 Hz interval using a Young anemometer placed at 3 m height at a nearby eddy covariance tower. The measured wind speed was used to estimate wind speed at 0.15 m above the soil using the relationship:

$$V = \frac{u^*}{0.4} \cdot \ln \cdot \left(\frac{(0.15 - d)}{z_m}\right)$$

where u^* is the friction velocity, d is the zero place displacement and z_m is the momentum roughness parameter. The hourly mean of $V(0.15)$ was then computed.

3. Results and discussion

Weather conditions during the comparison session between the two systems are reported in Figure 2: air temperature ranged between 6 °C at night and 19 °C at midday, air humidity during the experiment was around 30-40% and soil water content (% v/v) measured with five TDR sensors was stable and around 21%. Over the CO_2 efflux range of 0.5-4.0 μmol m^{-2} s^{-1}, the two system showed significant agreement at each chamber especially at low rates (Fig. 3.A; $P < 0.001$), but on average, the system we proposed overestimates the efflux by about 10% in comparison to LiCor 6400. However, the means of effluxes measured at the five chambers show a

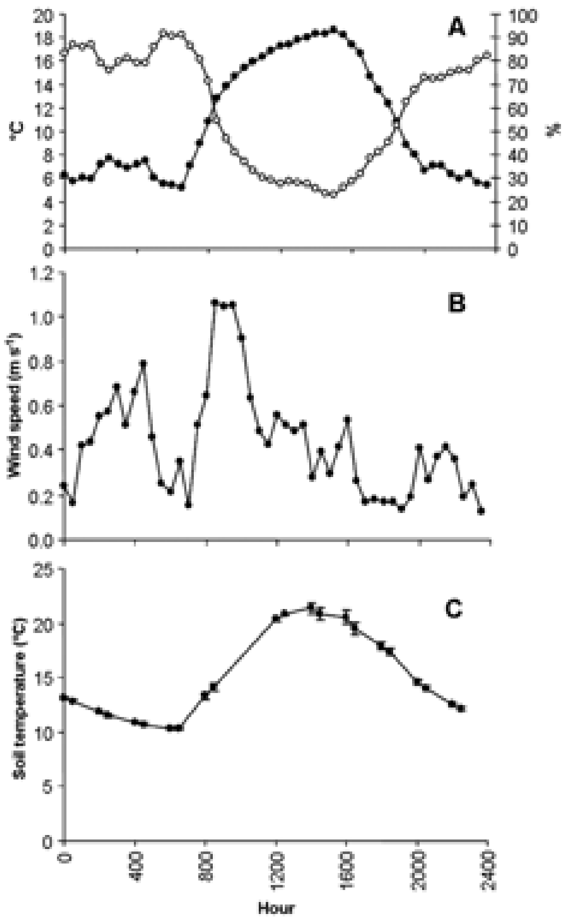

Figure 2. Air temperature and relative humidity (A), calculated wind speed at 0.15 m (B) and soil temperature (C) during the comparison between the two systems. Bars for the soil temperatures are standard error (n = 5). Measures are half-hourly average.

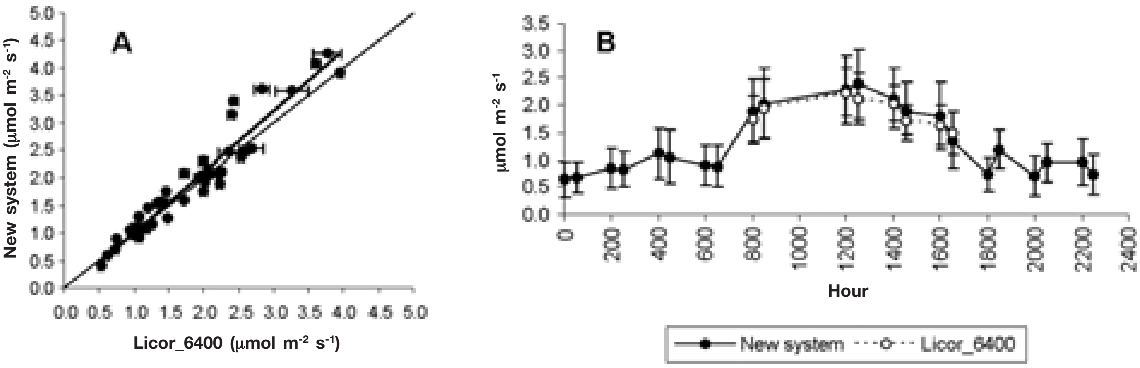

Figure 3.A. Soil CO_2 efflux as measured by the new system plotted against fluxes measured by the Li-Cor 6400 system (slope: 1.10; intercept: -0.08; n = 40; R^2 = 0.92; P < 0.001). Data points represent one measurement taken with the new system and the average of three consecutive cycles taken by the Licor 6400. Bars are standard errors (n = 3).
Figure 3.B. Efflux daily trend as measured by the two systems. Bars are standard errors (n = 5 chambers).

good agreement between the two system in terms of daily trend (Fig. 3.B).

The system worked properly during all the long term experiment period: some data gaps were only due to maintenance or very severe storms when the system was turned off, remotely. As far as the data quality is concerned, 261 efflux measurements on 2640 (10%) have been discarded because the regression was not good or the analyzer did not work properly (Tab. 1). During the field testing, higher soil CO_2 fluxes were recorded whenever there was wind during the measurement period. In figure 4.a and 4.b the correlation between soil CO_2 efflux and P' and between soil CO_2 efflux and wind speed are reported for a 5-days period. It is possible to noticed that when there is a rapid increase in *P'* due to a rapid increase in wind speed, the measured efflux is higher than during calm conditions. Takle et al. (2004) found a systematic increase in soil CO_2 fluxes with increasing pressure and mean wind speed. Kimball and Lemon (1972) demonstrated the influence of wind on water vapour fluxes through shallow soil but they concluded that diffusion is the dominant process altering soil aeration. Wind can also influence soil CO_2 efflux by two other mechanisms: the first is that wind influences the aerodynamic resistance to CO_2 transport near the soil surface; the second is that it

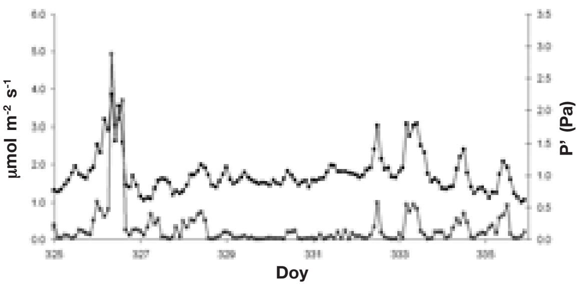

Figure 4.A. Soil respiration and pressure fluctuation (P') induced by wind at the experimental site from 21st November 2006 (doy 325) to 2nd December 2006 (doy 336). Each point is the average of data recorded during one measuring cycle.

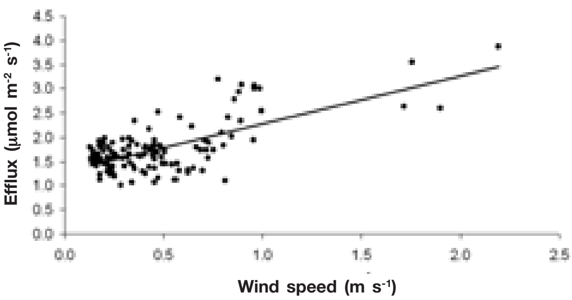

Figure 4.B. Soil respiration as function of mean wind speed at vent height from 21st November 2006 (doy 325) to 2nd December 2006 (doy 336). Each point is the average of data recorded during one measuring cycle (slope = 0.99, intercept = 1.30, R^2 = 0.46, n = 132, P < 0.001).

Table 1. Summary of the system performance during the long term test (from 17th Octber to 1st December 2006). One measurement cycle was performed every two hours.

Number of expected cycles	528	
Number of recorded cycles	493	93%
Number of high quality data	2379	90%
Number of discarded data	261	10%
Total number of recorded data	2640	100%

enhances mixing of the atmosphere removing respired CO_2 accumulated at the soil surface. An increase in wind speed determines a decrease in CO_2 ambient concentration thus enhancing the gradient between soil and atmosphere. As a consequence, a suddenly change in wind condition during lid closure may influence CO_2 target concentration thus causing an increase in efflux variability across chambers especially on bare soils.

4. Conclusions

The system we described in the present paper shows some advantages and some weakness when compared to other systems: reliable soil respiration measurements as demonstrated by the comparison with the Li-Cor 6400, reduced equipment costs, accuracies at high and low efflux rates, fully automated measurements and good suitability for long term continuous measurements campaigns. In particular, the vent design proposed by Xu et al. (2006) and implemented in the system allows the pressure to vary as gusts of wind cause the pressure within the surface soils to vary thus to measure effluxes representative of the entire ecosystem. As far as weaknesses are concerned, the critical aspect of the measurement is the CO_2 target concentration. In fact, in extreme conditions such as those during the long term campaign presented in this paper (i.e. absence of canopy, bare soil), gusts of wind during lid closure can influence the CO_2 target concentration thus causing an increasing efflux variability across chambers.

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