BRIEF COMMUNICATION

Comparison of CO_2 and H_2O fluxes over grassland vegetations measured by the eddy-covariance technique and by open system chamber

J. BALOGH[*], Z. NAGY[**], Sz. FÓTI[**], K. PINTÉR[**], Sz. CZÓBEL[**], E.R. PÉLI[*], M. ACOSTA[***], M.V. MAREK[***], Zs. CSINTALAN[**], and Z. TUBA[*,**]

Plant Ecology Research Group of Hungarian Academy of Sciences, Szent István University, Gödöllő, Hungary[*]
Department of Botany and Plant Physiology, Szent István University, Gödöllő, Hungary[**]
Institute of Systems Biology and Ecology, Academy of Sciences of the Czech Republic, Brno, Czech Republic[***]

Abstract

Measurements of CO_2 and H_2O fluxes were carried out using two different techniques—eddy-covariance (EC) and open system gas exchange chamber (OC)—during two-years' period (2003–2004) at three different grassland sites. OC measurements were made during fourteen measurement campaigns. We found good agreement between the OC and EC CO_2 flux values ($n = 63$, $r^2 = 0.5323$, OC $F_{CO2} = -0.6408+0.9508$ EC F_{CO2}). The OC F_{H2O} values were consistently lower than those measured by the EC technique, probably caused by the air stream difference inside and outside the chamber. Adjusting flow rate within the chamber to the natural conditions would be necessary in future OC measurements. In comparison with EC, the OC proved to be a good tool for gas exchange measurements in grassland ecosystems.

Additional key words: leaf area index.

Accurate measurements of CO_2 fluxes are necessary for understanding the carbon cycling of grassland ecosystems. Most of the studies on carbon cycling are based on meteorological methods—eddy covariance (EC) and Bowen ratio (Baldocchi *et al.* 1996, Saigusa *et al.* 1998, Frank and Dugas 2001, Sims and Bradford 2001, Suyker *et al*. 2003, Kato *et al.* 2004). Moreover, several chamber techniques are also in use (Oechel *et al.* 1998, Angell and Svejcar 1999, Steduto *et al.* 2002, Pavelka *et al.* 2004, Czóbel *et al.* 2005b). Despite the fact that chamber technique for gas exchange measurements is rather old (Reicosky and Peters 1977) there are still several problems with the chamber methods.

The advantages of the chamber methods are: (*1*) we exactly know where the average fluxes came from, while in the case of micrometeorological methods exact localisation of mean fluxes is not possible (although the probability density function for the total flux can be calculated by footprint analysis); (*2*) they provide information on the spatial physiological heterogeneity of the vegetation (Fóti *et al.* 2002); and (*3*) the lower cost acquisition compared to micrometeorological methods.

Most of the studies in soil respiration measurements used closed or open chamber (OC) techniques (Iritz *et al.* 1997, Pumpanen *et al.* 2004), however, micrometeorological methods are also used to measure soil respiration rate (Verma 1990). The chamber methods are often criticized (Leuning and Foster 1990, Dugas *et al.* 1997) because of the uncertainties of the chamber effects (temperature, radiation, and wind inside the chamber) and the

Received 29 May 2006, *accepted* 3 July 2006.
Fax: + 36 28 410804, e-mail: janko@fau.gau.hu

Abbreviations: C_d – CO_2 concentration difference; C_{out} – CO_2 concentration in the outlet tube; C_{ref} – CO_2 concentration in the inlet tube; e_d – water vapour pressure difference; e_{out} – water vapour pressure in the outlet tube; e_{ref} – water vapour pressure in the inlet tube; EC – eddy covariance system; F_{CO2} – CO_2 flux; F_{H2O} – H_2O flux; LAI – leaf area index; OC – open chamber system; P – atmospheric pressure; PAR – photosynthetically active radiation; SDH – standardized difference of H_2O fluxes;VPD – vapour pressure deficit.

Acknowledgements: The financial support by the MERCI Project (HPRI-CT-2002-000197), Greengrass (EVK2-CT-2002-00105), Carbomont (EVK2-CT-2001-00125), Carboeurope IP (GOCE-CT-2003-505572), KlimaKKT (NKFP6-00079/2005) and the research support granted to Z. Nagy in the framework of the Öveges József Program are gratefully acknowledged. We thank Mr. Attila Sóvári or the help in constructing the chamber. Opportunity to use the study area is acknowledged to the Kiskunság National Park and to Mr. Gábor Adamecz, the owner of the mountain grassland area.

non-continuous measurement. The most commonly used chamber method—the closed system with *Li-6200* infrared gas analyzer—has an additional drawback, as corrections for the CO_2 flux calculations are necessary (Hooper *et al.* 2002). In spite of all, they are frequently used due to low costs and ease of use (Dugas *et al.* 1997, Angell and Svejcar 1999, Steduto *et al.* 2002, Czóbel *et al.* 2005b). Moreover, measurements with OCs are seldom published. Even though, the Bowen ratio technique and the closed chamber system showed good agreement (Dugas *et al.* 1997, Angell *et al.* 2001); the chambers used during these studies did not allow continuous monitoring of the CO_2 gas exchange. Other studies on comparison techniques found the chamber fluxes generally lower relative to tower-based measurements (Oechel *et al*. 1998). Continuous measurements can be performed by automatic closed chamber system (Steduto *et al.* 2002). The open system chambers are simpler, however, since they do not need automated door-opening, it is easier and faster to perform the measurement even in special conditions (Czóbel *et al.* 2005a).

OCs are simpler to use than the closed chamber systems and the chamber effect is also smaller. The disadvantages of the OC system are the problems caused by the continuous air stream (different from the natural conditions), the pressure difference between the ambient air and the chamber's headspace, and sensitivity to the CO_2 concentration fluctuations in the reference air. The latter problem can be solved, however, by use of an averaging volume before the chamber, for example. The influence of the pressure difference on soil CO_2 efflux was reported by Fang and Moncrieff (1998), where CO_2 efflux decreased due to the positive pressure difference, but in natural conditions the pressure fluctuation range can be much higher (50–100 Pa) over grassland.

The OC method used in this study was developed to reduce the chamber effects when conducting continuous gas exchange measurement on field plots. Comparison of chamber flux measurements to parallel eddy covariance measurements was the main goal of the study.

The study was conducted on three different grassland sites in Central Europe. These fields were chosen for their differences, to be able to compare different situations: The grassland site Bílý Kříž, located in the Moravian-Silesian Beskydy Mountains in the Czech Republic (49°29′N, 18°32′E, 854 m a.s.l.), is a regularly mown mountain meadow. The mean annual air temperature is 5.5 °C, the mean annual precipitation range 1 100–1 140 mm. The soil is loamy sand with gravel. The grassland's main species are *Festuca rubra agg., Nardus stricta, Veronica officinalis,* and *Holcus mollis*. The Bugac site at Bugacpuszta (46°41'31"N, 19°36'06"E, 113 m a.s.l.), Hungary, represents one of the westernmost occurrences of the Eurasian steppe zone. The climate is temperate continental and the soil is a chernozem type sandy soil. The annual precipitation is 500 mm, the mean annual temperature is 10.3 °C. The vegetation is semi-arid sandy grassland, main species are *Festuca pseudovina, Carex stenophylla,* and *Salvia pratensis*. The study site is a part of the Kiskunság National Park and has been under extensive management (grazing) for the last 20 years. The Mátra site is situated in the Mátra mountain range (47.5N, 19.7E, 350 m a.s.l.). The soil is slightly acidic brown forest soil (clay) on volcanic base rock. The size of the grassland area in nearly plateau (horizontal) position is 200×300 m, slightly exposed to the west direction. The climate is continental with 600 mm annual sum of precipitation and 11 °C mean annual temperature. Main species are *Festuca valeisaca*, *Poa pratensis*, *Achillea collina*, *Lotus corniculatus*, and *Trifolium repens.*

At Bílý Kříž the EC system consisted of a *Gill Sonic R2* Anemometer/Thermometer and a *Li-COR 6262* Closed Path IRGA (*Li-COR*, USA). The *Edisol* software package (University of Edinburgh, UK) was used to calculate the fluxes of energy and scalars over the grassland. At Bugac and Mátra, the EC system consisted of a *Gill Sonic R2* Anemometer/Thermometer (Bugacpuszta) or a *CSAT3* anemometer (Mátra) and a *Li-Cor 7500* Open Path CO_2/H_2O IRGA (*Li-COR*, USA). The eddy flux data was calculated using the software described in Barcza (2001) and Barcza *et al*. (2003).

Net ecosystem exchange of CO_2 was measured regularly (seven times in 2003 and seven times in 2004) by using a portable IRGA (*CIRAS-2*, *PP Systems*, Hitchin, UK) and a 60-cm diameter hemispheric chamber, made from *perspex* fitted on a metal frame. Rubber band was fitted on the bottom perimeter of the chamber to prevent leaks. Collar was not used in this study. The chamber was placed over the plot continuously during the measurements. CO_2 and H_2O concentrations of the ambient (reference) air and that leaving the chamber headspace was sampled by 10 s. The ground surface area and height were of 0.2826 m^2 and 0.6 m, respectively, with a total volume of 0.11304 m^3. The air was blown through the chamber by an outer fan. The flow rates were 1.22–2.41 mol s^{-1}, depending on the grass height and leaf area index (LAI). The flow rates were calculated using the average wind speed and temperature measured by an anemometer at five points in the cross-section of the outlet tube. Measurements using OC were made at different plots by 14 measurement campaigns during two growing seasons (2003–2004) in all three sites.

C_{ref} and e_{ref} values were shifted +10 s compared to C_{out} and e_{out}, to account for the time lag between sampling for C_{ref} and C_{out} (in order to obtain maximum correlations between C_{ref} and C_{out}). This procedure was necessary, since averaging volume was not used before the chamber, resulting in small fluctuations in C_{ref} and e_{ref}. Spike removal was performed first by filtering data sets according to $-10<C_d<7$ [g m^{-3}] and $0<e_{diff}<3$ [mbar] (mainly caused by the operator's activites), then calculating averages and standard deviations for half hours and removing the data outside the interval given by the half-hourly average ± two times the half-hourly standard deviation.

The CO_2 fluxes were calculated from the half-hourly average of the filtered data by the following equation:

$$F_{CO2} = C_d\ f\ (1/S)\ [\mu mol(CO_2)\ m^{-2}\ s^{-1}]$$

where C_d is the CO_2 concentration difference between the chamber outlet and inlet [g m^{-3}], f is the flow rate of the air in the outlet tube [mol s^{-1}], and S is the surface area of the chamber [m^2].

The H_2O fluxes were calculated as follows:

$$F_{H2O} = (f(e_d))/(P - e_{out})\ (1/S)\ 1\ 000\ [mmol(H_2O)\ m^{-2}\ s^{-1}]$$

where f is the flow rate of the air in the outlet tube [mol s^{-1}], e_d is the water vapour pressure difference between the chamber outlet and inlet [mbar], P is the atmospheric pressure [mbar], e_{out} is the water vapour pressure of the outgoing air [mbar], and S is the surface area of the chamber [m^2].

The chamber was tested on polyethylene surface; the C_d and the e_d were measured as described above. Small, repeatable errors were detected in both cases, decreasing with increasing air flow. The dependence of errors on wind speed can be described by the following equations:

$$C_d\ \text{error} = -0.3653021914 + 0.0500806278\ w$$
$$e_d\ \text{error} = 0.0526122808 + -6.2085465199\ e - 3\ w$$

where w is the wind speed in the outlet tube [m s^{-1}]. The corrections of F_{CO2} and F_{H2O} values were performed by subtracting the estimated errors from the measured C_d and the e_d values.

The range of the PAR attenuation of the wall of the gas exchange chambers found in the literature is 10–20 % and depends on the position of the sun and the type of the material used in the chamber construction (Steduto *et al.* 2002). During this study the measured inside PAR/ outside PAR ratio was 86–92 %. The increase of temperature due to the chamber effect was not higher than 1 °C, and depended on the flow rate.

LAI was calculated from the sunfleck/PAR-transmittance values, using software written in *Excel* (*VisualBasic*) macro based on algorithms by Campbell (1986). Green leaf area was estimated from soil adjusted vegetation index, by using an agricultural digital camera (*ADC-2*, *Dycam*, Woodland Hills, CA, USA).

The measurements were done under various circumstances, the CO_2 fluxes obtained with OC compared well with the eddy fluxes under most of the conditions. The measured values of CO_2 flux rates by OC were in the same range as the EC ones. The available data have not shown relationship between the difference of the EC and OC F_{CO2} and the measured variables (*e.g.* SWC, temperature, wind speed).

The minimum and maximum values of half-hourly averages of CO_2 fluxes during this study were –0.04 and –10.34 μmol m^{-2} s^{-1} (EC), 1.08 and –9.73 μmol m^{-2} s^{-1} (OC) at Mátra site; 1.27 and –11.8 μmol m^{-2} s^{-1} (EC), 3.01 and –12.89 μmol m^{-2} s^{-1} (OC) at Bugac site; 0.06 and –7.37 μmol m^{-2} s^{-1} (EC), 0.01 and –5.8 μmol m^{-2} s^{-1} (OC) at Bílý Kříž site, respectively.

Fig. 1*A* shows the relationship between the two different methods based on the half-hour averages of CO_2 fluxes ($n = 63$, $r^2 = 0.5323$, OC $F_{CO2} = -0.6408 + 0.9508$ EC F_{CO2}). The scatter is large, because the EC technique got samples from larger grass patches from different directions, while the OC was measuring exactly the same plot throughout the measuring day. That is why the scatter was larger at the greater CO_2 uptake values, obtained mostly at the top of the vegetation period, where the appearance and photosynthetic performance of the vegetation was more diverse. The PAR attenuation of the chamber wall may have caused lower photosynthesis or higher respiration values at low irradiance.

The data sets of the H_2O fluxes were collected at Bugac and Mátra sites. In 2003 the amount of precipitation was considerably lower than in 2004 in each site, especially at the beginning of summer. The minimum and maximum values of half-hourly averages of H_2O fluxes during this study were 0.33 and 3.09 mmol m^{-2} s^{-1} (EC), 0.98 and 4.46 mmol m^{-2} s^{-1} (OC) at Mátra site, and 1.16 and 6.84 mmol m^{-2} s^{-1} (EC), 1.40 and 5.98 mmol m^{-2} s^{-1} (OC) at Bugac site, respectively.

As shown on Fig. 1*B*, the relationship between the two different methods based on the half-hour averages of H_2O fluxes ($n = 49$, $r^2 = 0.3255$, OC $F_{H2O} = 1.6603 + 0.4383$ EC F_{H2O}) is worse than that of CO_2; the values calculated after OC data were consistently lower than the same measured by the EC instrumentation. The scatter is large, but in most of the conditions the values of F_{H2O} were in the same range.

Dugas *et al.* (1997) described that the increased wind speed inside the chamber may increase the evaporation from the soil surface and cause relatively large evapotranspiration values compared to Bowen ratio method, while Steduto *et al.* (2002) and Reicosky *et al.* (1983) observed underestimation by the chamber. In our study, the OC H_2O fluxes were generally lower than the EC ones (Fig. 1*B*), especially in warm conditions at high evapotranspiration rates. Other factor contributing to the differences was the difference between the wind speed over the field and the air stream speed within the chamber.

Several variables were observed to find the solution of this problem. Focusing on the relationship between LAI and the standardized difference of the half-hourly OC and the EC F_{H2O} [SDH = (EC F_{H2O} – OC F_{H2O})/EC F_{H2O}] (Fig. 2), the results indicate the impact of the wind speed inside the chamber on the estimated evapotranspiration rate ($n = 25$, $r^2 = 0.3638$, SDH = –0.7027 + 0.198 LAI). Since the ventilator providing the air stream through the chamber was operated at a constant power, resistance to the air stream offered by the vegetation varied according to the amount of biomass (LAI) inside the chamber. Thus, higher LAI values resulted in smaller wind speeds in the chamber. On the other hand, wind speed in the chamber might have been higher than outside the chamber in low wind conditions.

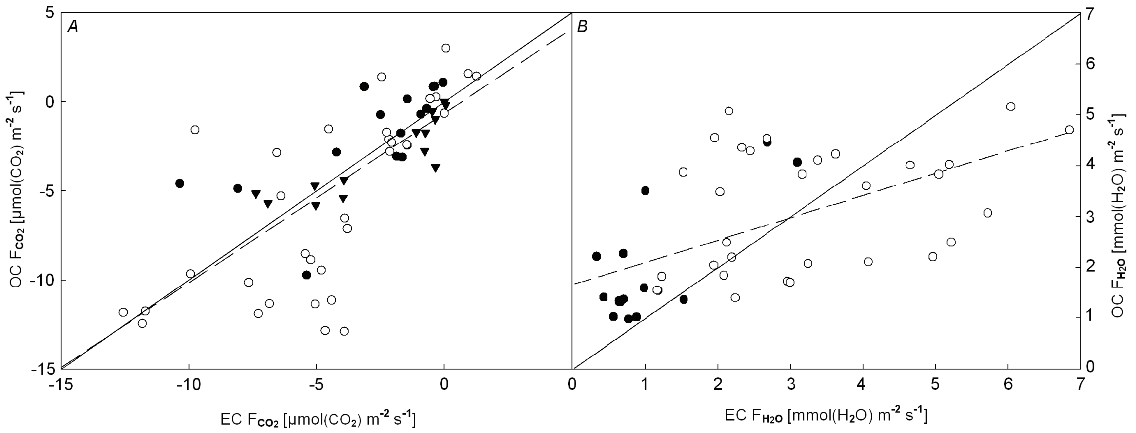

Fig. 1. Half-hourly CO_2 (*A*) and H_2O (*B*) fluxes as calculated using open chamber (OC) and eddy covariance techniques (EC) at Bílý Kříž (*triangle*), Bugac (*open circles*), and Mátra (*filled circles*). The 1 : 1 lines (*solid lines*) and the regression lines (*dashed lines*) are shown. Negative flux means uptake of CO_2.

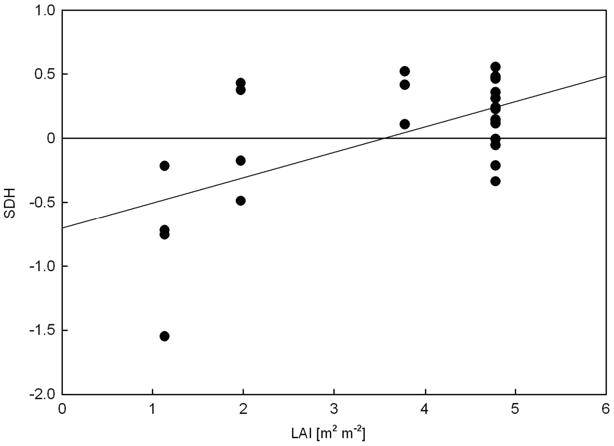

Fig. 2. The relationship between leaf area index (LAI) and standardized difference of H_2O fluxes (SDH) under well-watered conditions (*filled circles*) at Bugac site. Positive values mean underestimation; negative values mean overestimation by the OC compared to EC.

Under good water supply and at high LAI values, the SDH values showed positive correlation with LAI. However, when the LAI was low (at the beginning and at the end of the growing period) an overestimation was observed. A possible explanation of that are the higher evaporation and transpiration rates combined with lower wind speed at high LAI and high temperatures, resulting in smaller VPD inside the chamber than in the ambient air and therefore limiting evapotranspiration, while lower LAI (lower soil cover) allowed higher wind speeds in the chamber and higher evaporation from the soil surface, compared to the values measured by the EC. The overestimation by the chamber at low LAI is also shown in Fig. 2. This was presumably caused by the higher wind speed in the chamber (compared to outside).

These results suggest that the future OC gas exchange measurements need to set the wind speed inside the chamber continuously to the ambient (outside) wind over the vegetation surface. This could permit to make accurate measurements near to natural conditions.

On the base of the obtained results we conclude that the OC can be a useful device for gas exchange measurements, especially for short-time measurement campaigns. Under hot and dry conditions, frequent in summer, the OC system would be a better choice for gas exchange measurements than the closed one. The main reason for this could be that due to slow gas exchange rates under these conditions, one measurement in a closed system may take several minutes, and during this longer period significant and artificial gradients of temperature and concentrations of the measured gases will inevitably build up. The OCs are simpler without the automated door-opening system and it is easier and faster to set them up in the field.

The better agreement between the OC and EC measurements in the case of the CO_2 than the H_2O fluxes might have been caused by the much lower CO_2 concentrations compared to the H_2O ones. High and increasing H_2O concentrations coupled with slow air stream resulted in lower VPD in the chamber than in the ambient air. Flow differences might not have caused these differences, since in that case the discrepancy between the measured fluxes would have been similar for the two gases. The solution to this problem may lie in drying the reference air stream, but this procedure is difficult for relatively large air volumes used in this system.

Adjusting flow rates in the chamber to match those under natural conditions would be necessary to increase the reliability of chamber measurements. Eliminating the boundary layer resistance in the chamber during leaf scale measurements is not an option in case of large chambers and high LAI values. The problem of finding the proper wind speeds at heights lower than the vegetation height may be solved by use of miniature wind sensors.

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