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Automated Monitoring of Soil Respiration: A Moving Chamber Design

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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 chamber that would permit monitoring of CO_2 efflux rates over long time periods without altering the natural microclimate within the chamber. Furthermore, the design would permit accurate measurements even in a highly fluctuating CO_2 environment. We built a chamber that operates by closing over the soil in response to a control signal and remains closed for a 14-min period before opening again. Thus, the chamber allows normal drying and wetting of the soil between measurements. An automated switching system was programmed to sequentially open and close chambers in concert with an infrared gas analysis system (IRGA). The IRGA was operated in a differential mode, and equivalent flow rates of reference gas (ambient air) and sample gas (air exiting chamber) were maintained with mass flow controllers. A flexible neoprene lid, stretched tightly over each chamber when closed, provided an airtight seal. This feature and the use of a large mixing bottle (for buffering frequent changes in ambient CO_2 concentration) permitted us to measure soil CO_2 efflux rates even in an environment with highly variable atmospheric CO_2 concentration. Soil respiration rates, measured over a period of several weeks with the automated chambers, were in agreement with traditional point-in-time measurements, and the soil microclimate was not affected by the chambers. However, when extrapolated over a period of several weeks the point-in-time measurements overestimated CO_2 efflux rates based on continuous measurements with the automated system.

Soil respiration is a very large fraction of gross primary productivity in terrestrial ecosystems, and its quantification is a high priority in attempts to establish ecosystem C budgets (Reichle 1981: Franzluebbers et al., 2002). Raich and Schlesinger (1992) estimated that CO_2 efflux from soils exceeded CO_2 release from combustion of fossil fuel by an order of magnitude. Hanson et al. (1993) presented data from several forests in the USA and Europe showing soil CO_2 efflux rates ranging from 0.6 to 3.9 kg CO_2 m^{-2} yr^{-1}.

Yet the rates that have been reported in the literature were obtained by a variety of measurement techniques, and measurement techniques can influence the apparent rates of respiration. Jensen et al. (1996) reported highly nonlinear results between rates of CO_2 efflux measured with numerous static techniques and a dynamic technique in forest soils at several sites in Denmark and Sweden.

The current emphasis on ecosystem management for increased C sequestration mandates improved monitoring of soil respiration. If CO_2 flux from the soil cannot be accurately measured, models that use gas exchange measurements to predict the long-term dynamics of soil C pools will remain deficient. The importance of quantifying rates of CO_2 efflux from soils was recently accentuated by the European Science Foundation's workshop that addressed the problems associated with measurements of soil respiration (European Science Foundation, 2000).

The primary problem facing strategies for measurement of soil respiration is the tremendous spatial and temporal heterogeneity in the rates of soil CO_2 efflux (e.g., Xu and Qi 2001). Rates of CO_2 efflux vary over the course of a day, mostly in response to changing soil temperature, and seasonally in response to root growth phenology, litter inputs, temperature, and moisture. Currently, this variation is often handled by establishing temperature response relationships, which are then applied to point-in-time measurements of CO_2 efflux and continuously monitored soil temperature, or air temperature if soil temperature is not available. This procedure is subject to errors because other factors that influence soil respiration are not taken into account. For example, soil respiration will be higher when roots are actively growing than when they are not, even if the temperature is the same. Soil moisture also affects respiration rates as well as gaseous diffusion. Spatial heterogeneity in soil CO_2 efflux can be handled by making many replicate measurements, but because each measurement takes some time, the spatial variation becomes confounded with temporal variation. Our objective was to develop, construct, and test an automated open-flow system that will provide high temporal resolution measurements of CO_2 efflux continuously over long time periods without altering the natural microclimate of the soil. The gases evolving from the soil must be moved with the ambient air stream at constant and quantifiable flow rates sequentially through several chambers inverted over the soil surface to an appropriate analysis system. The analysis system must accurately monitor concentration differences of the gases in the air before entering (reference air) and after exiting the chambers (sample air). This is especially difficult in an environment of highly fluctuating CO_2 concentration such as at forest free-air CO_2 enrichment (FACE) facilities. A previous design (Edwards, 1974), in which the entire chamber is alternately raised and lowered over the soil surface was not adequate for performing soil respiration measurements at the Oak Ridge FACE facility because it would not seal against the soil surface well enough to prevent interference by the highly fluctuating CO_2 concentration surrounding the chamber. Another problem with the Ed-

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Abbreviations: IRGA, Infrared gas analyzer; FACE, Free-air CO_2 enrichment; Q_{10}, the change in the rate of respiration with a 10°C change in soil temperature (i.e., a Q_{10} of 2 means that the rate doubles with a 10°C temperature change).

wards (1974) system was that it alternately measured CO_2 concentration in a chamber inverted over the soil and a chamber without soil, and the differences in the two concentrations provided an estimate of CO_2 efflux rates. This design does not perform well in a situation where ambient atmospheric CO_2 concentration varies greatly over short time intervals. We built and tested a chamber, which, based on out tests, permits accurate monitoring of soil CO_2 efflux even in highly fluctuating CO_2 environments.

MATERIALS AND METHODS

Chamber and Switching System Description

The chamber consists of an Al cylinder (20 cm diam. by 15 cm depth) open on both ends, a hinged neoprene lid for the cylinder, a small electric motor with a push-rod for opening and closing the lid, and a switch which is remotely activated to turn on the motor (Fig. 1). The bottom of the cylinder is sharp so that it can be pushed into the soil to form a reasonably good seal between the inside of the chamber and the atmosphere. Two adjustable legs permit positioning the chamber on uneven soil surfaces. When closed the elastic neoprene lid stretches tightly over the top of the cylinder forming an airtight seal. An electric pump pulls air through a 0.4-cm diam. plastic tube (sample line) from the chamber to an IRGA. The tubing is connected to a manifold mounted inside the chamber about 5 cm above the soil surface. The manifold, which serves as an air mixer, is protected from rainfall by a small metal shield when the chamber is in the open position. Air enters the chamber through a 2.5-cm diam. intake port on the opposite side from the manifold. Originally the intake port was only 0.50 cm in diameter and this resulted in negative pressure within the chamber based on pressure readings at a port in the side of the chamber. We were able to reduce CO_2 efflux rates by increasing the size of the intake port (Fig. 2). Rates were near stabilization when the inside diameter of the intake port was at least twice that of the exit port. There was a very slight reduction in CO_2 efflux rates when the opening was enlarged to a 2.5-cm diam. Because of relatively low sensitivity of the pressure gauge used, we were able to detect slight pressure reduction within the chamber only when the intake port was 0.5 cm in diameter and smaller. However, we assumed that the reduced rates with larger opening were because of attaining pressure equilibrium between the inside and outside of the chamber. Based on these measurements we used a 2.5-cm diam. plastic tube to connect from the intake port to an 18-L mixing bottle. Air enters the mixing bottle through a 2.5-cm diam. hole, covered with a fine mesh screen, in the bottom of the bottle. The mixing bottle is positioned about 50 cm above ground level. Air is also pumped through a 0.4-cm diam. plastic tube (reference line) from the mixing bottle directly to the IRGA, bypassing the soil chamber.

After testing a single prototype chamber, seven additional chambers were built at a cost of about $800 per chamber. An automated switching system (CR10X Measurement and Control System, Campbell Scientific, Logan, UT) was programmed to sequentially open and close the chambers in concert with the IRGA system. The IRGA was a LiCor 6252 (LiCor Inc, Lincoln, NE). Each LI-6252 was connected in tandem to a LI-800 IRGA, which monitored only reference gas concentrations. The reference gas concentration data were fed directly into the LI-6252. This was necessary to correct for the nonlinear response of the LI-6252 analyzer to changing reference gas concentrations at the FACE. The chambers operated by closing over the soil in response to a control signal and remained closed for a preset time interval before opening again. Two mass flow controllers located on the pump-side of the IRGA maintained equal airflow rates through the sample line and the reference line. The mass flow controllers were periodically calibrated using a soap film bubble technique (Gilian Gilibrator 2 Calibration System, Sensidyne, Clearwater, FL). Carbon dioxide concentrations in the sample line and reference line were measured with the IRGA operating in differential mode and concentration values were recorded as Δ [CO_2].

The automated system was tested over a period of several weeks in a 14-yr-old sweetgum (*Liquidambar styraciflua*) monoculture at the Oak Ridge National Laboratory's FACE facility (Norby et al. 2001). We monitored soil respiration at

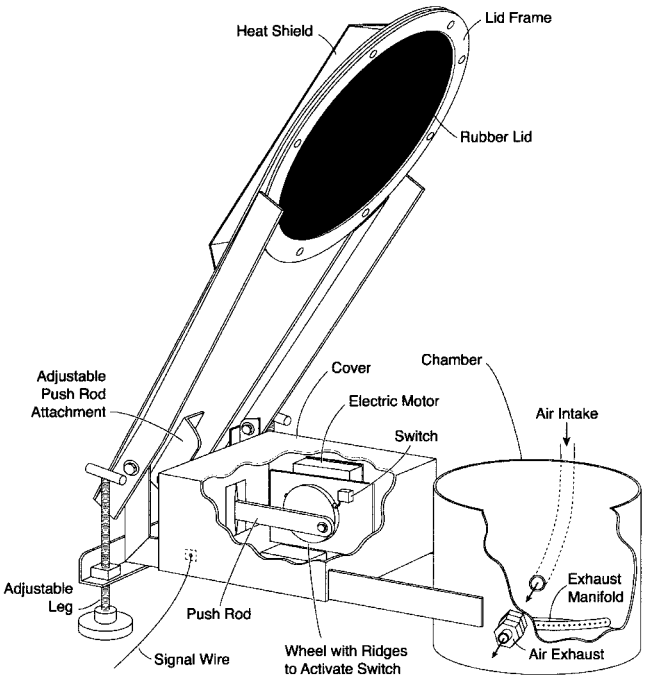

Fig. 1. A drawing of the soil respiration chamber shown in the open position.

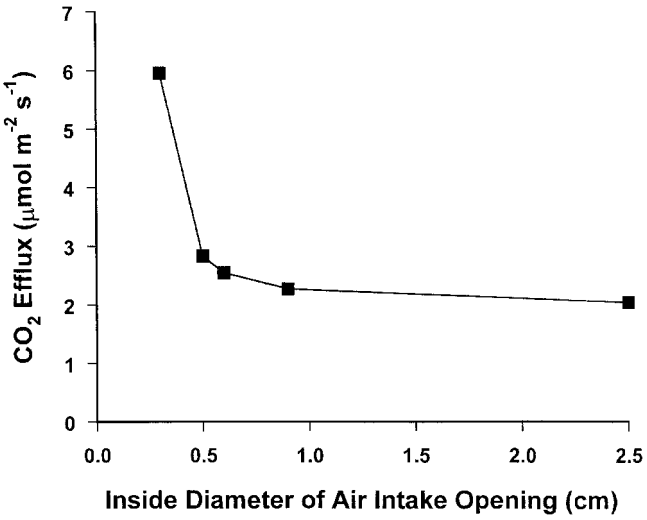

Fig. 2. Soil CO_2 efflux rates as affected by changing the size of the intake opening on the chamber.

the FACE with four automated chambers in two control rings and four automated chambers in two high-CO_2 rings. We used two 16-port manifold and valve systems (MAC Valves Inc., Wixom, MI). One system and four automated chambers were used in the control rings. The second system and four automated chambers were used in the high-CO_2 rings. We also acquired point-in-time measurements at six permanently established locations adjacent to the automated chambers in each ring at about 2-wk intervals to better evaluate spatial variability. The point-in time measurements were performed with a closed-loop system and a model 6250 IRGA (LiCor Inc, Lincoln, NE).

Field Tests

Air was pumped through all chambers and airlines continuously during both chamber-open and chamber-closed positions. The flow rates were maintained at about 0.5 L min^{-1} when chambers were open with air bypassing the IRGA and at 0.9 L min^{-1} during the sample period while chambers were in the closed position. We found that about 12 min was required to reach equilibrium in ΔCO_2 values after chamber closure. Therefore, each chamber was signaled to close 12 min before data logging began. During operation a chamber was signaled to close while the previous chamber was still being measured. This enabled us to obtain measurements every 7 min even though each chamber remained closed for a total of 14 min. The 16-port manifold and valve system was programmed to direct airflow through each set of reference and sample lines in sequence for 7-min intervals. Four of the 16 ports were used for testing the soil respiration chambers and the other 12 were left for measuring CO_2 exchange rates in other parts of the ecosystem or for expanding the number of soil chambers. Each chamber was measured for a 7-min period with only the last 2 min recorded. During the last minute of the 2-min period the reference air and the sample air were switched whereby the IRGA cell that had received sample air during the first minute received reference air during the last minute and vice versa. The ΔCO_2 value during the 2-min measurement period was corrected for instrument drift as follows:

$$\text{Corrected } \Delta CO_2 = \Delta CO_2 + \text{Drift}$$
$$\text{Drift} = x - (x + y/2)$$

where x represents the average ΔCO_2 during the first minute and y represents the average ΔCO_2 during the second minute. This procedure helped to alleviate problems with instrument drift and reduced the frequency of calibration requirements. We found that calibration every 2 wk was adequate under normal operating conditions.

Thermocouples for measuring air and soil temperature inside the chamber were inserted through ports on the chamber wall. Temperatures were measured at 10 cm above the soil surface and at 8 cm below the soil surface. Temperature measurements were taken at the same positions outside the chamber. Soil moisture was measured with a time domain reflectometer (TRASE systems, Soil Moisture Equipment Corp., Santa Barbara, CA) using permanently installed vertical waveguides that integrate measurements over the depth interval from 0 to 20 cm (Topp and Davis, 1985). Soil moisture was measured at about 2-wk intervals in each chamber and adjacent to each chamber throughout the test period. Temperatures and ΔCO_2 values were recorded simultaneously every 7 min.

The field test results presented below are from the high-CO_2 rings only.

RESULTS

Initial tests revealed that daytime air temperatures inside the chamber increased slightly during the 14 min after closing. This was corrected by constructing a reflective roof over the neoprene lid. After the reflective roof was installed, there were no detectable differences between air and soil temperatures measured just before closing and at the end of the 14-min closure period (Fig. 3).

Measurement of CO_2 exchange in the high CO_2 FACE rings presented a challenge because of fluctuating CO_2 concentration both spatially and temporally. We used an 18-L mixing bottle on the intake side of each of the respiration chambers to buffer these changes in CO_2 concentration. We had found that a 3.5-L mixing bottle provided an adequate buffer in the control rings. The mixing bottles and the airtight lids of the respiration chambers permitted stable measurements of soil CO_2 efflux rates that fluctuated in concert with diurnal changes in soil temperatures (Fig. 3).

The automated chambers were operated for several weeks without altering the soil moisture (Fig. 4). Soil respiration rates measured with the automated chambers that were taken at the same time as the point-in-time measurements were in close agreement (Fig. 5 and 6) during an 8-wk period in 2001. However, over the 8-wk period, the averaged point-in-time measurements were 21% higher than the averaged automated measurements (Table 1). Establishing a Q_{10} value (the change in the rate of respiration with a 10°C change soil temperature) and a base rate for the point-in-time measurements and using continuously monitored soil temperatures to predict respiration rates narrowed the difference in the averages to 4%.

DISCUSSION AND CONCLUSIONS

Most chambers that have been used for continuously monitoring soil gas efflux alter the microclimate of the soil and therefore have the potential to alter the rates of respiration and gas efflux. Schwartzkopf (1978) used an automated system for measuring soil respiration but with chambers that remained closed except for periodic manual removal. Rayment and Jarvis (1997) found that an open-system soil respiration chamber could be used continuously for no more than about 3 d before moisture evaporating from the soil began to condense on the chamber lid. Fang and Moncrieff (1998) used a similar design to that of Rayment and Jarvis (1997) except that the chamber was open at the top allowing air as well as rainfall to enter the chamber. The chambers introduced by Rayment and Jarvis (1997) and by Fang and Moncrieff (1998) solved problems related to pressure effects on CO_2 efflux, but did not permit natural drying over long-term measurement periods. Edwards (1974) also observed wetting and drying problems associated with stationary chambers and demonstrated that chambers left in place affected CO_2 efflux rates. Edwards (1974) then introduced the first moving chamber design for measuring soil respiration.

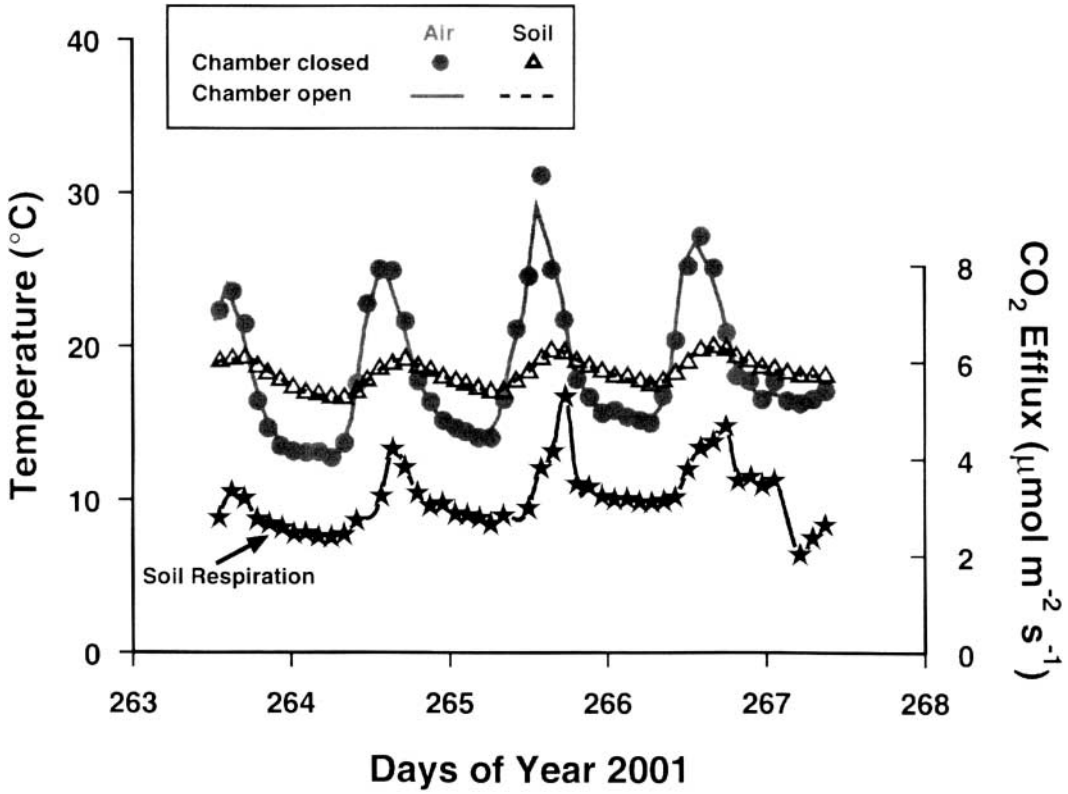

Fig. 3. Air temperatures and soil temperatures at the 8-cm depth in both the open and closed positions. Temperatures with the chamber closed were recorded during the last minute of a 14-min period of chamber closure. Temperatures with the chamber open were recorded approximately 1 hr after the chamber was opened. Soil respiration rates from the same chamber are also shown.

The chamber design presented here embodies improvements over that of Edwards (1974). The primary improvement is a relatively airtight design. The airtight design permits measurements even in environments with highly fluctuating ambient CO_2 concentration, such as at FACE sites. The airtight design should also permit measurements with a closed-loop system and an IRGA set in the absolute mode. This would require plumbing modifications, but would eliminate the need for a mixing bottle, and only one mass flow controller would be required for each analyzer. Another advantage of using a closed-loop system would be reduced chamber closure time, because the rate of increase in CO_2 concentrations within the chamber could be recorded shortly after closure of the chamber lid rather than waiting for steady state to be reached as in the open system. Time required for steady state in the automated chamber could also be reduced by making the chamber more shallow thereby reducing the air volume.

Goulden and Crill (1997) reported the successful use of an automated gas exchange system and moving chambers at the moss surface of a black spruce forest. Their chambers utilized a simple manifold for mixing the air, but required daily calibrations by standard additions of a known concentration of CO_2. This calibration was used to account for IRGA response, chamber volume, and leaks with the atmosphere. Our system requires a calibration no more than once per week (typically every 2 wk) under normal operating conditions, and the soil chambers are simple and virtually leak proof. Soil respiration rates measured over a period of several weeks followed expected diurnal and seasonal patterns, and soil moisture and temperature remained the same inside and outside the chambers.

The advantage of automated moving chamber systems over point-in-time measurements is evident in this study. The difference between average CO_2 efflux rates between the two systems over a 2-mo time period (Table 1) can be explained in part by the fact the manu-

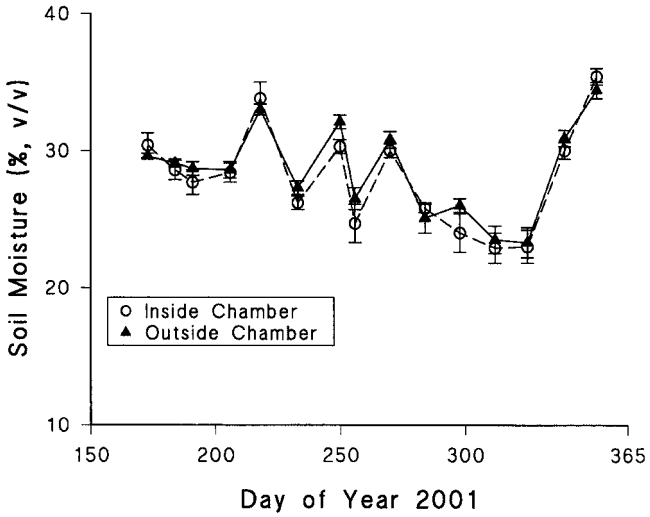

Fig. 4. Soil moisture changes over a 7-mo period in 2001 inside the automated chambers (n = 4) and adjacent to the chambers (n = 12). Values are means and standard errors.

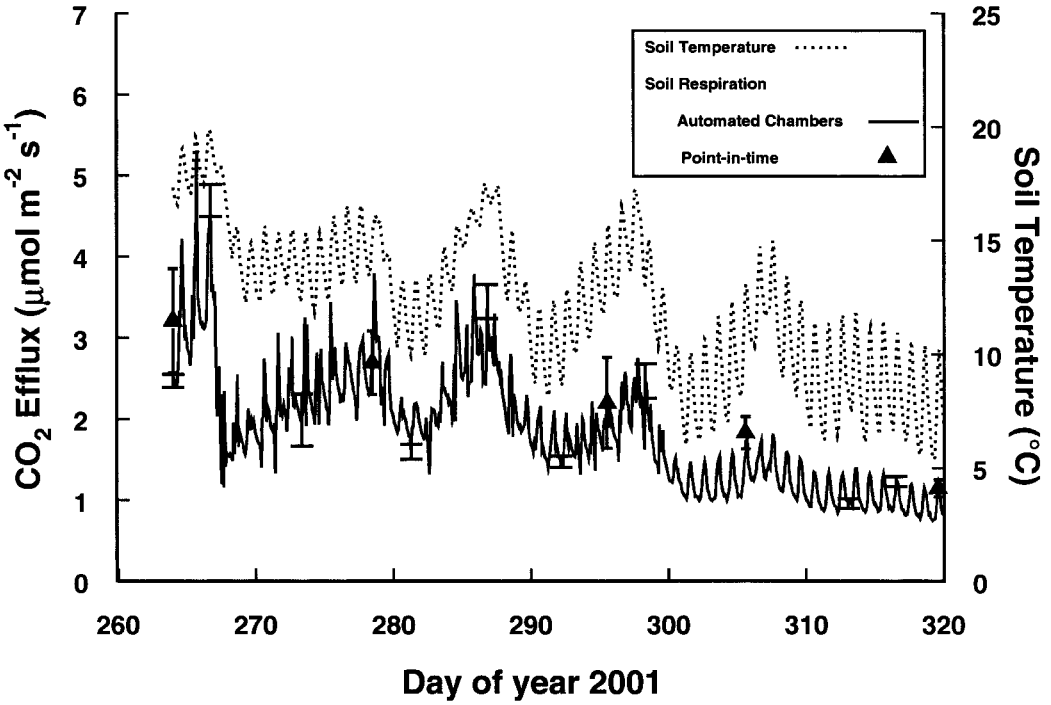

Fig. 5. Soil respiration and soil temperature recorded every 110 min over an 8-wk period beginning in mid-September, 2001. Data are means of four automated soil chambers. Standard error bars are shown at periodic time intervals for the automated system. Also shown are the means and standard errors (n = 12) of five point-in-time measurements taken with a closed system infrared gas analyzer (IRGA) adjacent to the soil chambers.

ally measured rates were taken during the day when rates are expected to be higher than at night when temperatures were lower. This points to the need for point-in-time measurements to be made more than once per day to capture the temperature differences that are the primary drivers of diurnal variations as suggested in a recent workshop that dealt with problems associated with measuring soil respiration (European Science foundation, 2000). Care must be taken when establishing Q_{10} values and base rates to make long-term predictions from point-in-time measurements because both may change during the course of a year, especially in climates with highly varying microclimatic conditions and phenological events. In this study, the Q_{10} predicted rates from the point-in-time measurements were only 4% higher than the rates measured with the automated system, but the moisture conditions varied little during the 8-wk period and we were at or near the end of the growing season. The point-in-time measurements are acceptable for making comparisons of treatment responses within a carefully planned regiment of measurements. However, an automated moving chamber system eliminates most of the uncertainties associated with point-in-time measurements and temporally changing respiration rates. Data from point-in-time measurements are especially problematic when used for helping to establish whole

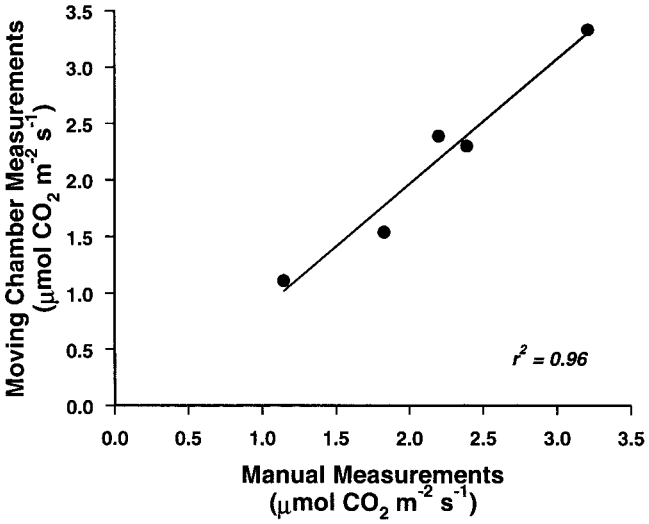

Fig. 6. A comparison of soil respiration rates measured with the automated open flow system and the stationary closed-loop system. Each data point represents the mean rates measured with the automated chambers (n = 4) and the mean rates manually measured with stationary chambers (n = 12) during the same time period.

Table 1. Comparison of rates of soil respiration determined with the automated open flow moving chamber system and the manual closed-loop point-in-time system. Measurements were made in a sweetgum plantation in Tennessee from 21 Sept. through 15 Nov. 2001.

	Average CO_2 efflux	
	Measured	†Predicted
	μmol m^{-2} s^{-1}	
Automated system	1.83	1.82
Manual system	2.21	1.91

† The calculated Q_{10} value (change in the rate of respiration with a 10°C change in soil temperature) for the automated system was 2.98 and the base rate at 15°C was 2.29 μmol CO_2 m^{-2} s^{-1} (r^2 of soil temperature vs CO_2 efflux = 0.81). The calculated Q_{10} value for the manual system was 3.10 and the base rate at 15°C was 2.43 μmol CO_2 m^{-2} s^{-1} (r^2 of soil temperature vs CO_2 efflux = 0.87).

ecosystem C budgets. A moving chamber design as described here, while more expensive than manually operated systems, provides more reliable data for use in establishing ecosystem C budgets. Also, the amount of data collected per hour worked probably outweighs the cost of the equipment.

Dynamax Inc. (dynamax.com), 10808 Fallstone, Ste 350, Houston, TX 77099 USA, is planning a commercial version of the automatic soil chamber. Dynamax may be contacted about interest in the new design.

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REFERENCES

Edwards, N.T. 1974. A moving chamber design for measuring soil respiration rates. Oikos 25:97–101.

European Science Foundation. 2000. Investigating the role of soils in the terrestrial carbon balance—Harmonizing methods for measuring soil CO_2 efflux. European Science Foundation LESC Exploratory workshop. 6–8 Apr. 2000. Edinburgh, UK.

Fang, C., and J.B. Moncrieff. 1998. An open-top chamber for measuring soil respiration and the influence of pressure difference on CO_2 efflux measurement. Ecology 12:319–325.

Franzluebbers, K., A.J. Franzluebbers, and M.D. Jawson. 2002. Environmental controls on soil and whole-ecosystem respiration from a tallgrass prairie. Soil Sci. Soc. Am. J. 66:254–262.

Goulden, M.L., and P.M. Crill. 1997. Automated measurements of CO_2 exchange at the moss surface of a black spruce forest. Tree Physiol. 17:537–542.

Hanson, P.J., S.D. Wullschelger, S.A. Bohlman, and D.E. Todd. 1993. Seasonal and topographic patterns of forest floor CO_2 efflux from an upland oak forest. Tree Physiol. 13:1–15.

Jensen, L.S., T. Mueller, K.R. Tate, D.J. Ross, J. Magid, and N.E. Nielsen NE. 1996. Soil surface CO_2 flux as an index of soil respiration in situ: a comparison of two chamber methods. Soil Biol. Biochem. 28:1297–1306.

Norby, R.J., D.E. Todd, J. Fultz, and D.W. Johnson. 2001. Tree response to rising CO_2 in a CO_2–enriched sweetgum stand. New Phytol. 150:477–487.

Raich, J.W., and W.H. Schlesinger. 1992. The global carbon dioxide flux in soil respiration and its relationship to climate. Tellus 44b:81–99.

Rayment, M.B., and P.G. Jarvis. 1997. An improved open chamber system for measuring soil CO_2 effluxes in the field. J. Geophys. Res. 102:28779–28784.

Reichle, D.E. 1981. Dynamic Properties of Forest Ecosystems. Cambridge University Press. London.

Schwartzkopf, S.H. 1978. An open chamber technique for the measurement of carbon dioxide evolution from soils. Ecology 59:1062–1068.

Topp, G.C., and J.L. Davis. 1985. Measurement of soil water content using time-domain reflectrometry (TDR): A field evaluation. Soil Sci. Soc. Am. J. 49:19–24.

Xu, M., and Y. Qi. 2001. Soil-surface CO_2 efflux and its spatial and temporal variations in a young ponderosa pine plantation in northern California. Global Change Biology 7:667–677.