A multichannel automated chamber system for continuous measurement of forest soil CO₂ efflux

NAISHEN LIANG,¹,² GEN INOUE¹ and YASUMI FUJINUMA¹

¹ CGER, National Institute for Environmental Studies, Tsukuba, Ibaraki 305-8506, Japan
² Author to whom correspondence should be addressed (liang@nies.go.jp)

Received November 22, 2002; accepted January 21, 2003; published online July 15, 2003

Summary  We developed a fast-response multi-chamber system for measuring soil-surface CO₂ efflux (Fₖ). The chambers (90 × 90 × 50 cm, L × W × H) had lids that opened and closed automatically, and were connected in parallel to a single CO₂ analyzer equipped with a 16-channel gas sampler. Between measurements the chamber lids were raised to allow precipitation and leaf litter to reach the enclosed soil surface. When a chamber was closed, it was ventilated with well-buffered ambient air (125 l min⁻¹) that entered by an inlet on one chamber sidewall and exited through a large vent on the opposite sidewall. The pressure difference between the inside and outside of the chamber was less than 0.22 Pa. Two additional mixing fans maintained an air speed of 0.3 ± 0.1 m s⁻¹ at 20 cm above the soil surface. Air was withdrawn continuously from the inlets and outlets of each chamber, and fed sequentially to an infrared CO₂ analyzer. With this system, we measured Fₖ in a 40-year-old temperate Pinus densiflora Sieb. & Zucc. forest from February 8 to May 30, 2001. Mean Fₖ increased steadily from 0.9 µmol m⁻² s⁻¹ at the beginning of February to 4.6 µmol m⁻² s⁻¹ by the end of May. There was a statistically significant correlation between Fₖ and surface soil temperature (r = 0.896; P < 0.0001), and the Q¹₀ value was 2.8. Spatial variation of Fₖ was higher in the non-growing season than in the growing season. Measurements were not interrupted by either rain or snow.

Keywords: AsiaFlux, flux chamber, Pinus densiflora, soil temperature, spatial variation.

Introduction

Soil-surface CO₂ efflux (Fₖ) has recently been identified as the largest component of ecosystem respiration and the second largest component among ecosystem carbon budgets, and is thus the main determinant of carbon balance in terrestrial ecosystems (Valentini et al. 2000). It is estimated that, on average, 60 to 80% of the carbon sequestered by tree canopy photosynthesis is lost to the atmosphere by Fₖ (Baldocchi et al. 1997, Goulden et al. 1998, Kellner et al. 1999, Valentini et al. 2000, Law et al. 2001). Therefore, accurate measurement of Fₖ is critical for estimating the carbon cycle dynamics of an ecosystem. However, for technical reasons, there are many uncertain ties and limitations associated with direct estimation of Fₖ. Approaches that have been adopted include the use of static and dynamic chambers, micrometeorological methods (such as eddy covariance), and soil CO₂ gradient methods. The soil CO₂ gradient technique, which requires estimation of soil transport coefficients as well as measurement of CO₂ concentrations at different soil depths, has not been used widely. The eddy covariance technique typically requires specific atmospheric and topographical conditions. Previous studies have shown that it generally underestimates Fₖ from the forest floor during the day and overestimates Fₖ during the night, because it integrates soil CO₂ efflux, gas exchange of the understory vegetation and bole respiration (Baldocchi et al. 1997, Law et al. 1999). Janssens et al. (2000) concluded that the eddy covariance technique was unsuitable for estimating Fₖ in forest ecosystems with dense undergrowth.

The measurement of Fₖ in forests has normally relied on one of four chamber-based techniques: (1) static chambers containing either an alkali solution (Kirita 1971) or soda lime (Biscoe et al. 1975) to absorb the respired CO₂; (2) static chambers from which samples are removed with a syringe and subsequently analyzed by gas chromatography (Loftfield et al. 1992); (3) closed dynamic chambers in which the CO₂ concentration increase is monitored and numerically evaluated (Rochette et al. 1991, Healy et al. 1996); and (4) open dynamic chambers that are coupled to an infrared gas analyzer (IRGA) (Rayment and Jarvis 1997, Fang and Moncrieff 1998, McGinn et al. 1998). Some studies have compared measurements with static and dynamic chambers. Dynamic chambers are generally considered more accurate than static chambers (Nakayama 1990, Rochette et al. 1992, Nay et al. 1994, Janssens et al. 2000), and can be operated as either closed or open systems. Rigorous field tests (Norman et al. 1997) and model calculations (Conen and Smith 2000, Rayment 2000) indicate that Fₖ values measured with closed systems are often about 10% less than those measured with open systems because a proportion of the respired CO₂ is stored within the soil profile while the chamber is in place. However, both static and closed dynamic techniques give periodic measurements, which are often used with linear interpolation to estimate daily Fₖ. Errors can be large, because Fₖ patterns between measurements are not al-
ways predictable, and vary with the time of day (McGinn et al. 1998, Rayment and Jarvis 2000). However, automated dynamic chamber systems, which allow repeated measurements throughout the day, may provide accurate daily estimates of $F_c$ despite temporal variability (Jensen et al. 1996, Fang and Moncrieff 1998, McGinn et al. 1998). McGinn et al. (1998) designed an automatically opening and closing chamber for use in grassland, and obtained $F_c$ estimates that were significantly less than those obtained with the commercial Li-Cor closed dynamic chamber. Fang and Moncrieff (1998) developed an open-top chamber for use in forests and reported large variability in $F_c$ measured in the field as a result of fluctuations in wind speed and ambient CO$_2$ concentration near the soil surface.

Most closed or open chamber systems measure $F_c$ at only one location (Fang and Moncrieff 1998). Several automated systems have been developed recently for continuous sequential measurement of $F_c$ at several sites within the AmeriFlux (Law et al. 2001) and CARBOEUROPE networks (IERM, Edinburgh University). But these systems comprise only a few (generally 3–6) small ($\leq 0.20$ m$^2$) chambers. High spatial and temporal variability of $F_c$ has been found in relatively uniform agricultural fields (Rochette et al. 1991), grassland (McGinn et al. 1998), forests (Kellihier et al. 1999, Rayment and Jarvis 2000, Xu and Qi 2001), and even on bare soil (Nakadai et al. 2002), indicating the need for large numbers of samples and sampling locations to obtain a representative value of $F_c$ for an ecosystem (Xu and Qi 2001). Furthermore, when measuring forest floor $F_c$, chamber placement, e.g., relative to tree stems, needs to be considered. Fang and Moncrieff (1998) recommended use of a fast-response chamber that could easily be moved between locations. However, because it requires time to move and re-equilibrate a chamber, this approach is severely limited.

Prolonged continuous measurement of $F_c$ at a single location with a closed chamber system modifies the environment by excluding precipitation and raising the temperature, among other effects (reviewed by Norman et al. 1997, Janssens et al. 2000). Moreover, pressurization anomalies associated with open-flow dynamic chambers are a source of measurement error. A pressure difference has a greater effect on a small chamber than on a large chamber because of a larger edge effect (Norman et al. 1997, Lund et al. 1999).

Based on the results of the studies cited, we designed a fast-response, 16-chamber automated system to continuously monitor $F_c$ at different locations within a forest ecosystem with a single IRGA that successively measures gas samples from each chamber.

**Description of the automated system**

We developed a large, multi-chamber, automated system, similar to that described by Liang and Inoue (2001) and Liang et al. (2003), for measuring $F_c$ with a 16-channel gas sampler, a single, field-portable infrared gas analyzer (IRGA), and a laptop PC or data logger (Figure 1).

**Automated chambers**

The chambers (0.9 × 0.9 × 0.5 m, L × W × H) are made from clear PVC (1 mm) glued to a frame of extruded PVC (30 × 30 mm, 3 mm) (Figure 2). The chambers have PVC lids (3 mm) hinged at the sidewalls. The edges of the lids are reinforced with a closed-cell PVC strip (5 × 5 mm). A closed-cell polyurethane rubber gasket (20 × 5 mm) is attached to the underside of the lid, on the inside of the PVC strip, to ensure a gas-tight seal with the chamber wall and a closed-cell PVC strip glued across the center of the chamber where the lids meet.

Each lid is attached to the piston of a pneumatic cylinder (MCS300, Techno Fronto, Hitachi, Japan) mounted on a strip of PVC (5 × 60 × 900 mm) traversing the chamber 10 cm above the soil surface. The lids are raised to the vertical or closed by the action of the pistons, which are operated by air from a compressor (MAX-E-12, Techno Fronto) regulated by a four-way valve (BK120, Techno Fronto). Two micro fans (KMFH-12B, Kyoei, Tokyo, Japan) inside each chamber maintain air movement when the chamber is closed. Two additional fans, mounted on the lid, provide convective cooling when the chamber is open.

When a chamber is closed, approximately 125 l min$^{-1}$ of well-buffered ambient air is drawn into it through a PVC accordion pipe (25 mm in diameter) by a micro fan blower (TCF-12, Techno Fronto) located at an inlet on the chamber side wall. The buffers (5.0 m$^3$) are made of plastic-coated steel pipe (1.2 × 1.2 × 3.5 m, L × W × H) (Figure 1). Chamber air is emitted through a 100-mm-diameter downward-pointing elbow opposite the air inlet.

**Multichannel gas sampler**

The multichannel gas sampler comprises two valve manifolds (APM210-16, Techno Fronto) each with 16 three-way solenoid valves, a 16-channel relay driver (ER-16, National Instruments, Austin, TX), two purge pump unions (each consisting of four 5-l min$^{-1}$ pumps, CM-50, EMP, Tokyo, Japan), and two 1.5-l min$^{-1}$ sampling pumps (CM-15, EMP). The sampler has dimensions of 40 × 35 × 20 cm high, a minimal internal volume and a continuous air flow in all intake lines to minimize the time required to switch between air samples taken from different chambers. The airflow arrangement of the sampler is shown schematically in Figure 3. The ambient air and chamber air are withdrawn continuously from all 16 chambers, but only the air from the closed chamber is pumped to the IRGA (LI-6262, Li-Cor, Lincoln, NE). Two purge pump unions ($P_a$) withdraw ambient air and chamber air, separately, from the 15 chambers not being measured; two sampling pumps withdraw the ambient air ($P_a$) and chamber air ($P_c$) from the measurement chamber. The ambient and chamber airstreams are taken from the chamber inlet and outlet, respectively, and balanced by mass flow controllers (SEF-21A, STEC, Kyoto, Japan), and then passed through water traps to the IRGA (Figure 3). The water traps remove condensation in the tubing. The polyurethane tubes (6 × 4 mm; Type US-4, Nitta Moor, Tokyo, Japan) that draw air from each chamber are of the same length to
equalize the resistance to flow and ensure the same lag time for all chambers. The CO₂ permeability and water absorption of the tubes are negligible. Each intake line is equipped with a 100-µm plastic Millipore filter (Swinnex-13, Millipore, Bedford, MA).

Soil-surface CO₂ efflux is calculated as:

\[
F_c = \left( C_s - C_R \right) \frac{Q \times 10^3}{V_{\text{air}}} \frac{1}{A}
\]

where \(C_R\) and \(C_s\) are ambient and chamber CO₂ concentrations (µmol mol⁻¹) measured from the inlet and outlet of the chamber, respectively; \(Q\) is volume flow rate through the chamber (m³ s⁻¹); \(A\) is soil surface area covered by the chamber; and \(V_{\text{air}}\) is molar volume of air. The values of \(F_c\) from the 16 chambers are averaged over 1 h.

Over the course of an hour, the chambers are closed sequentially by the 16-channel relay driver controlled by the laptop PC or data logger, and the air sampled. The PC or data logger acquires output from the IRGA (Figure 3).
Testing the system

Testing response time of the multichannel gas sampler

The response time of the multichannel gas sampler was evaluated to assess the time required to remove the air from the previous chamber before recording data from the next chamber (cf. Xu et al. 1999). The sampler was set up by feeding the 16 reference intakes CO₂-free dry air while the 16 sample inlets were fed two standard gases of different CO₂ concentrations (347.7 and 599.8 µmol mol⁻¹; Sumitomo Seika Chemicals, Yachiyo, Japan). The channels were set to switch between the solenoid valves every 15 s, and the flow was set to 1.0 l min⁻¹. The interval between data transmissions through the RS-232C port was 0.5 s, and the response in the output of the IRGA was recorded on the PC at 1-s intervals. The resulting time course of changes in CO₂ concentration is depicted in Figure 4a. The first portion of the time course, lasting slightly longer than 1.5 s, represents measurement of the stationary air originally present in the intake of the first valve and the downstream flow path, including the tubing and cells of the sampling pump, flowmeter and IRGA. Only after a total time lapse of 6 s from the opening of the first valve was the measurement fed into the channel. The subsequent lower and higher plateaus represent measurements of the two standard gases of known CO₂ concentrations. Figure 4a shows that there was a delay of about 6 s after switching to the next channel before the LI-6262 IRGA output registered the beginning of the change in concentration. Because the response time of the IRGA is short, most of the delay is caused by the air from the previous sample remaining in the flow path downstream of the 3-way solenoid valve (Figure 3). Time was required to purge this path segment of the old air. Once the fresh air reached the IRGA, it took about 0.5 s to achieve a new steady output, mostly because of the time required to displace the old air in the sample cell of the IRGA and replace it with new air.

To test the water vapor response of the sampler, the 16 sample inlets were fed with two airstreams with humidities of 18.7 and 33.5 mmol mol⁻¹. Water vapor was controlled by two dew-point generators (LI-610, Li-Cor). Measurements were taken by following the same procedure used to test CO₂, except that the sampling period for each channel was set to 5 min. The beginning of the change in IRGA output after switching was delayed by a lag time similar to that for CO₂, but more time was required to reach the new steady output (Figure 4b). This was
likely because of the absorption and release of water vapor by the wall materials of the flow pathway. However, the delay time could be shortened by increasing the flow of sample air as well as by warming the wall of the flow pathway (data not shown).

**Measurement accuracy and equilibration times**

The time taken for the chamber CO₂ concentration to reach a steady state (equilibration of the chamber) varied with chamber volume and flow rate. The two chamber mixing fans gave a wind speed of 0.3 ± 0.1 m s⁻¹ at 20 cm above the soil, as measured with an anemometer (Model 6521, Kanomax Japan, Osaka, Japan) at nine points on a 20 × 20 cm grid. The wind speed in our chambers was lower than in the commercially available LI-6400-09 (Li-Cor) and SRC-1 (PP Systems, Hitch, Hertfordshire, U.K.) closed dynamic soil chambers. At 1 cm above the soil, wind speed in these chambers is 0.4 and 0.9 m s⁻¹, respectively (Le Dantec et al. 1999). Mean wind speed at 0.5 m above the floor in a northern larch (Larix kaempferi Sarg.) forest at the Tomakomai CO₂ flux site in Hokkaido, Japan, in 2001 was reported to be 0.4 m s⁻¹ (summer) to 0.6 m s⁻¹ (winter) (Liang et al. 2003). We assume, therefore, that the wind speed in our chambers did not greatly affect forest floor CO₂ VAR. Variability in wind speed above the forest floor may influence transport of CO₂ from the litter layers (Le Dantec et al. 2000). However, extensive field study with wind speeds ranging between 0 and 2.8 m s⁻¹ showed that wind speed had no effect on CO₂ in forests (J. A. Subke, University of Bayreuth, and R. Navarro, Harvard University, unpublished data).

A test of measurement accuracy and system equilibration was conducted in a plastic box measuring 120 × 120 cm wide and 60 cm high. The box was filled to 50-cm depth with dried (at 105 °C) forest mineral soil to provide a porous medium through which CO₂ could diffuse. A chamber was placed on the soil covering 56% of exposed soil surface area. Pure CO₂ was injected at 19.353 ml min⁻¹ (corresponding to an Fc of 10 µmol m⁻² s⁻¹) into the bottom of the box through a spiral of PVC pipe (10 × 8 mm) with 1 mm holes every 3 cm to simulate soil CO₂ emission. Well-buffered air was blown into the chamber at 115 l min⁻¹ and the difference in CO₂ concentration between outlet and inlet was measured (Figure 5). The time to reach a steady-state chamber CO₂ concentration (Figure 5) was fitted by the gas diffusion law:

$$\Delta C_t = \left(1 - e^{-\frac{V}{Q}}\right) \frac{F_c}{Q}$$  \hspace{1cm} (2)

where ΔC is the CO₂ concentration difference between the chamber inlet and outlet at time t; V is volume (mol) of the chamber; and Q is molar flow rate through the chamber (mol s⁻¹). Tests indicated that the CO₂ concentration in the chamber took approximately 20 min to equilibrate, which was consistent with the theoretical time course (Figure 5). The measured CO₂ difference was 98.1% of that calculated according to Equation 2 after 21.5 to 22.5 min. This ratio of 98.1% was used to calibrate the field measurements.

![Figure 5. The time to reach a steady-state CO₂ concentration difference between the inlet and outlet of the chamber following chamber closure. Circles represent measured CO₂ concentration differences. The line shows the fitted curve. Pure CO₂ was injected into the bottom of the box at a flow rate of 10 µmol m⁻² s⁻¹. Air flow through the chamber was set at 115 l min⁻¹.](http://heronpublishing.com)

**Test of differential pressure**

In our automated system, the micro fan driving air into the chamber through the 15-m PVC pipe is typically run at a constant 12 V DC, and the flow rate is ≤ 125 l min⁻¹, i.e., about one chamber volume every 3 min. Flow rate can be decreased by reducing the fan power supply. The flow rate was evaluated by measuring the wind speed inside the PVC pipe with an anemometer (6521, Kanomax Japan) and calculating the cross section of the pipe. Because the big vent had low resistance to air flow, the pressure difference between inside and outside was 0.22 ± 0.02 Pa under windless conditions in the laboratory. The pressure difference was measured with a micro-differential pressure transducer with a resolution of 0.01 Pa (PX163, Omega Engineering, Stamford, CT). The pressure in our chamber is slightly higher than ambient air pressure, similar to that of the LI-6400-09 soil chamber (0.2–0.3 Pa), but much lower than that of the SRC-1 (1.4 ± 0.4 Pa) (Le Dantec et al. 1999). Moreover, a field test at wind speeds between 3 and 5 m s⁻¹ showed that the pressure excess inside our chamber had decreased to ≤ 0.19 Pa as a result of wind passing the vertical outlet.

**Test of temperature increase inside the chamber**

To limit solar heating, most chambers are made of opaque reflective materials, e.g., stainless steel, aluminum, and PVC (LI-6400-09, SRC-1; Rayment and Jarvis 1997, Fang and Moncrieff 1998, Janssens et al. 2000, Law et al. 2001). Because of the high light transmission characteristics of clear PVC, temperature inside our chambers was significantly higher than ambient outside air temperature. The observed temperature increase, measured with shielded thermocouples, was up to 15 °C when the chamber was installed on grass in the open at an ambient temperature of 30–35 °C (Figure 6), and there was condensation on the chamber walls when the chamber was closed. However, the temperature increase was only about 3 °C in 50% shade (Figure 6) and there was no conden-
Generally, solar irradiance at the forest floor is less than 20% of full sunlight (Liang et al. 2001), so chamber heating is likely to be small during measurements on the forest floor.

Measuring soil CO$_2$ efflux in a forest ecosystem

To check the accuracy of our system under field conditions, we set it in a 40-year-old temperate Pinus densiflora Sieb. & Zucc. forest on the campus of the National Institute for Environmental Studies, Tsukuba, Japan, at the end of January 2001. The 16 chambers were placed randomly on the forest floor within an area 30 m across. The length of the polyurethane tubing used to sample air from each chamber was 20 m. Because the equilibration time of the chamber was less than 20 min, it was possible to finish a cycle of measurements within 1 h by closing six chambers at the same time. The air from the first chamber was pumped to the IRGA, while the other five chambers equilibrated. We set the sampling period for each chamber to 225 s. After the channel had changed, there was a delay of 165 s for total flushing of the tubing and IRGA before the CO$_2$ was measured at 5-s intervals over the next 60 s. Therefore, during a 1-h measurement cycle, each chamber was closed for 22.5 min. During the closure, we observed no condensation on the chamber walls (irradiance was low, about 10% of full sunlight). One chamber served as a control to calibrate the system in situ, i.e., to set the zero and range of the IRGA. The control chamber was fixed to a plastic plate to exclude soil CO$_2$, and constant flows of buffered air and buffered air mixed with pure CO$_2$ were fed into the chamber during each cycle. Thus, the measured results from the other 15 chambers could be calibrated every 2 h against the two points from the control chamber.

The soil temperature inside the chambers was measured at 5-cm depth and at 30-min intervals from March 6 (Day 65) to May 30, 2001 by means of recording thermometers with internal sensors (TR-51A, T & D, Nagano, Japan).

Soil CO$_2$ efflux in a temperate Pinus ecosystem

Figure 7 shows the hourly mean (15 chambers) seasonal changes in soil CO$_2$ efflux and soil temperature in the Pinus forest from February 8 to May 30, 2001. The discontinuity in $F_c$, occurred because of an error in programming the laptop PC. Soil temperature is an abiotic variable that affects $F_c$. Estimated mean $F_c$ was 0.9 ± 0.3 µmol m$^{-2}$ s$^{-1}$ in February. The spatial variation in $F_c$ among the 15 chambers was high, with a mean coefficient of variation (CV) of 48%. Total CO$_2$ efflux from the forest floor is assumed to consist of the contributions of microbial respiration and root respiration. In winter, however, it is postulated that the upper limit of forest-floor $F_c$ will be set by the quantity of living roots (Kelliher et al. 1999). The high spatial variability of $F_c$ was caused by heterogeneity of root distribution (Thierron and Laudelout 1996). We found higher values of $F_c$ with the chambers that covered the soil surface at 0.2–1.5 m from the tree stems and lower $F_c$ with the chambers that were set farther from the tree stem (> 2 m). This spatial pattern of $F_c$ is consistent with previous observations made with small dynamic chambers (Kelliher et al. 1999, N. Liang, unpublished data). As the surface soil temperature increased, mean $F_c$ increased steadily to 4.6 ± 0.7 µmol m$^{-2}$ s$^{-1}$.
at the end of May, because the mild temperatures stimulated both microbial activity and root metabolism. However, the CV of \( F_c \) decreased to 27%, suggesting a proportionally lower spatial variation of \( F_c \) in the growing season than in the non-growing season. Moreover, the diurnal course of \( F_c \) showed good agreement with the daily trend of soil temperature at 5-cm depth (Figure 8). The range of diurnal \( F_c \) variation was larger on sunny days than on cloudy days, because of the larger diurnal variations in surface soil temperature on sunny days. Over the whole measurement period, the correspondence between forest floor \( F_c \) and surface soil temperature was significant (\( R = 0.897, P < 0.0001 \), Figure 8). The soil CO\(_2\) efflux quotient, \( Q_{\text{obs}} \), was 2.8. This value lies in the middle of the range for a variety of forest soils (cf. Xu and Qi 2001).

Many studies have shown a positive correlation between \( F_c \) and soil water content (e.g., Kelliher et al. 1999, Xu and Qi 2001). During our field study, \( F_c \) increased suddenly and greatly following rainfall. However, it returned to a lower value by the next day. This result and our extensive measurement of \( F_c \) at the Tomakomai CO\(_2\) flux site (Liang et al. 2003) suggest that the rapid increase in \( F_c \) following rainfall is caused by displacement of CO\(_2\) from soil spaces by rainwater.

Conclusions

Our present results and previous field evaluations of the Li-Cor soil chamber system, open-top chamber system and soil CO\(_2\) gradient technique (Liang et al. 2003) indicate that the multichannel automated chamber system is effective for continuous measurement of forest-floor CO\(_2\) efflux, even on snowy and rainy days. It can provide a large amount of high-quality data on soil CO\(_2\) efflux from the forest floor. For example, it can estimate soil CO\(_2\) efflux over a large surface area and simultaneously evaluate both spatial and temporal variation. We have used this system to gather \( F_c \) automatically at several sites, from tundra in central Siberia to tropical forests in Southeast Asia, within the AsiaFlux network since spring 2001 (e.g., Liang et al. 2003). The cost of the system is low, because it uses only a single CO\(_2\) analyzer for the 16 chambers. The whole measuring system, except for the chambers and buffers, can be assembled in a single field-portable package (70 × 50 × 35 cm) (see Figure 1). Mean power consumption of the MGS-16 is 23 W; each chamber consumes less than 4 W during measurement; the IRGA and data logger use about 10 W and 1 W, respectively; and the air compressor temporarily (10 min every 9 h) consumes 32 W. Therefore, the maximum power consumption of the whole system is about 70 W.

The only maintenance required is calibration of the IRGA and measurement of the flow rate through the chambers. However, because the system runs in the steady-state mode, it has several limitations when used for long-term continuous measurements of soil CO\(_2\) efflux. The chamber takes up to 20 min to achieve a steady state; it excludes some leaf litter and rainwater; and it may modify the chamber environment relative to the ambient conditions over the long term. In particular, when the system is used for the measurement of soil CO\(_2\) efflux in forest gaps or in field crops or grassland, the 125 l min\(^{-1}\) flow rate through the chambers is insufficient to prevent significant solar heating (Figure 6). This heat effect could be severe because soil CO\(_2\) efflux is temperature-driven in most ecosystems. Moreover, a small pressure difference (≤ 0.22 Pa) between the inside and outside of the chamber results in underestimation of soil CO\(_2\) efflux. However, these disadvantages can be eliminated by operating the system in a closed-path mode. This shortens the closure time for each chamber to 2–3 min, because a steady state need not be reached. As a result, modification to the soil condition inside the chambers is minimized, because the chambers are open for at least 95% of the time over a 1-h measurement cycle. Moreover, the pressure difference between inside and outside the chamber can be minimized in the closed-path analysis because the chambers are connected in closed circuit to the IRGA. Mean power consumption can be lowered to 15 W in this modified approach. A combination of two 75-W solar panels and three 150 Ah true deep cycle marine batteries has been found sufficient to power the system at study sites without electricity.

Acknowledgments

We are grateful for financial support from the Global Environment Research Program of the Ministry of the Environment of Japan. We thank the AsiaFlux Steering Committee for encouragement during development of the multichannel automated chamber system. We acknowledge Ming Xu (Rutgers University) and Dennis Baldocchi’s research group (University of California, Berkeley) for critically reviewing the manuscript.

References


