A System for the Measurement of Vertical Gradients of CO$_2$, H$_2$O and Air Temperature within and above the Canopy of Plant

Ahmed Al-Saidi¹, Yasunori Fukuzawa¹, Noboru Furukawa², Masami Ueno², Shigeyuki Baba³ and Yoshinobu Kawamitsu²

¹The United Graduate School of Agricultural Sciences, Kagoshima University, Kagoshima 890-0065, Japan; ²Faculty of Agriculture, University of the Ryukyus, Okinawa 903-0213, Japan; ³Tropical Biosphere Research Center, University of the Ryukyus, Iriomote, Okinawa 907-1514, Japan

Abstract: This technical report describes a gradient system for characterizing the vertical gradients of CO$_2$, H$_2$O, and air temperature within and above the canopy of plants. The system is low in cost and easy to use. The instruments were fitted and placed in one box with a total weight of about 10 kg. The box can be carried and moved from one site to another. The features of this apparatus are high frequency sampling cycle as short as 1 min per cycle for all six measurement levels and fast response gas analyzer for measurement as short as 10s per level. Two exhaust pumps, one sampling pump, six 3-way solenoid valves, and flow meter were used to insure simultaneous flow rate of air in all tubes from all measurement levels. This system transfers data from the data-logger directly to the add-in Spreadsheet of Microsoft Excel by using an Ethernet cable to automatically convert digital data to scientific units in less time. This system also allows the use of multiple micro-environmental sensors that can be sampled at the same time. It is useful not only for agricultural ecosystems but is also adequately sensitive and rapidly responds to the gas analyzer with a modifiable flow rate meter for use in forest ecosystems. This system also has potential for use in the measurement of CO$_2$, H$_2$O, associated environmental elements, and CO$_2$ storage flux within the canopy of plant, and other processes including a CO$_2$ sink and source.

Key words: CO$_2$ profile, Gradient system, H$_2$O concentration, Light intensity.

The emission of CO$_2$ during the consumption of industrial fossil fuel increases atmospheric CO$_2$ concentration, whereas photosynthesis decreases CO$_2$ on the local, regional, and latitudinal scales. Photosynthesis is a very important process not only for plant growth but also for maintaining global carbon balance. Photosynthetic carbon assimilation is dependent on the canopy-air CO$_2$ concentration, which is an essential driving parameter of mechanistic models built to predict plant responses to changing environmental conditions (Rasse et al., 2002). CO$_2$ fluctuates in canopy air and diffuses from downward fluxes from the atmosphere and upward fluxes from the soil surface. The temporal fluctuations of micro-environmental factors affect the distribution of CO$_2$ concentration within the canopy air, but their variation is not understood (Maitani and Seo, 1986). Measurement of diurnal variations in CO$_2$ and H$_2$O concentrations and air temperature within the canopy of plant is required for various eco-physiological investigations. To date the most common approach for measuring photosynthesis is usually based on extraction of volumes of air from a closed system cuvette containing a leaf over a set time interval. The CO$_2$ content of the gas volumes is determined with an infrared gas analyzer, and the photosynthetic rate is calculated from the cuvette CO$_2$ concentration depletion rate (e.g. Ehleringer and Cook, 1980). CO$_2$ and H$_2$O concentration, air temperature, and photosynthetic photon flux density are the fundamental drivers of photosynthesis. In the field, these drivers may vary with the time of day, stand type, canopy height and specific locations. Furthermore, these drivers may also vary within the air layers of the canopy. The canopy of C$_4$ and C$_3$ crops and trees interacts differently with their surrounding environment. This may be because the photosynthetic ability of the leaf differs even among varieties within the same species as well as with the species and with the group, C$_4$ or C$_3$ (Murata, 1981). In the tropical and subtropical regions, C$_4$ species show far higher productivity than C$_3$ species. The photosynthetic intercellular CO$_2$ response curve and light response curve are usually determined under a controlled environment. However, the drivers that affect these curves may diurnally vary within the air layers of the canopy. To our knowledge, little information is available about the diurnal change in the vertical profiles of CO$_2$, H$_2$O, and air temperature within and above the canopy of C$_4$ and C$_3$ crops and trees. These vertical profiles are very important and prerequisite for studying photosynthesis. Therefore, the vertical profiles of drivers of photosynthesis within
the canopy may provide reproducible data. These data can be linked with the photosynthetic intercellular \( \text{CO}_2 \) response curve and light response curve to understand the dynamics of photosynthesis under field conditions. Furthermore, continuous measurement of vertical gradients of \( \text{CO}_2 \), \( \text{H}_2\text{O} \), and associated micro-environmental parameters, is important for studying the plant environment and plant responses to environment and measurement of \( \text{CO}_2 \) fluxes.

Several methods are available for measuring gas exchange between vegetation and atmosphere and they vary in both spatial and temporal measuring aspects (Goulden et al., 1996; Hollinger and Richardson, 2005). One popular technique is the micrometeorological system (Goulden et al., 1996; Chunlin et al., 2007). Micrometeorological systems generally measure fluxes between vegetation and atmosphere using environmental parameters above the canopy of plants (Wilson and Meyers, 2001). However, micrometeorological systems made above the forest canopy have limitations. The measurement of \( \text{CO}_2 \) flux using the eddy covariance system does not always represent the net ecosystem exchange during the period of sampling (Ruimy et al., 1995; Grace et al., 1995; Wilson and Meyers, 2001). This is because of the \( \text{CO}_2 \) storage in the layer of air below the measurement level. The canopy storage change has been adequately accounted for as part of the net ecosystem exchange determination (Gu et al., 2005). The importance of \( \text{CO}_2 \) storage flux to the net ecosystem exchange is due to the accumulation of \( \text{CO}_2 \) within the canopy airspace during a calm night, which may be depleted in the early morning as the turbulence intensity increases (Grace et al., 1995). For the determination of \( \text{CO}_2 \) storage flux, it is very important to measure \( \text{CO}_2 \) concentration profile at different heights near the ground level (Gu et al., 2005).

There are still few high-precision techniques for vertical profile measurement of \( \text{CO}_2 \) within and above a forest canopy (Murayama et al., 2005). The analyses of variations in a vertical \( \text{CO}_2 \) profile are very useful for understanding the ecosystem processes (Bazzaz and Williams, 1991) and the biological activities (Kumagai et al., 2001). There are, therefore, increased requirements for the development and design of a non-destructive system for measuring vertical gradients of micro-environmental elements within and above the canopy of plants. In this technical report, we describe a non-destructive system for measuring \( \text{CO}_2 \), \( \text{H}_2\text{O} \), and air temperature gradients along and discuss its main features.

**Description of the gradient system**

**A design of the system**

(1) **Closed path subsystem**

Fig. 1 shows the schematic diagram of the gradient system. The gradient system was tested for over one year at different ecosystems, such as sugarcane and sorghum fields. In the sugarcane field, the area of the field was about 100 m\(^2\) with a mean canopy height of about 2 m. The spacing of plants within the row was about 25 cm and the spacing between rows was about 120 cm. In the sorghum field, the area of the field was about 70 m\(^2\) with a mean canopy height of about 3 m. The spacing of plants within the row was about 20 cm and that between rows was about 50 cm. There was a difference in density and canopy structure between sugarcane and sorghum. Because the height of the sampling inlet tubes depends on the height of the plant canopy, the inlet tubes in the sorghum field were suited to higher levels than that in the sugarcane field. The soil type was Okinawa soil with chemical fertilizer without application of compost.

Vertical gradients of \( \text{CO}_2 \) and \( \text{H}_2\text{O} \) were measured using a single infrared gas analyzer (LI-840, Li-Cor) to guarantee non-variations resulting from instruments. The infrared gas analyzer was calibrated in the laboratory by using a zero \( \text{CO}_2 \) standard and 400 \( \mu\text{mol} \)
mol$^{-1}$ certified span before and after the measurement period, and the change was negligible. Six inlet tubes ($6 \times 8$ mm) with a plastic filter to remove dust and water were set at six heights (0, 1, 2, 3, 4, and 5 m) in the sorghum field, and at five heights (0, 0.7, 1.4, 2.1, and 6 m) in the sugarcane field along the tower. In the sugarcane field, one inlet tube was used for sucking air from the soil chamber.

In the gradient system described here (Fig. 2), six 3-way solenoid valves (USG3-6-1, CKD), one valve for each level, controlled by a Steeping Rely (G9B-12, Omron) were used to switch between valves so that the monitoring level was sampled. Two exhaust pumps were used to ensure the simultaneous flow rate of air through all the inlet tubes of all levels while a sampling pump was used to suck the air from monitoring level. The flow meter (FD-A10, Keyence) was used to control, adjust and check the flow rate of air through the common sampling tube to ensure the simultaneously flow rate pass through the gas analyzer for measurements. The flow meter was installed between the sampling pump and gas analyzer and adjusted to around 1 L min$^{-1}$. In Fig. 2, the first 3-way solenoid valve (measured levels that being sampled) is switched so that air samples from the monitoring height of the tower is sucked by the sampling pump, pass through flow meter, pass through filter tube and then to gas analyzer for measurements. Subsequently, all five valves (for five levels not being sampled) were switched so that air is exhausted by two exhaust pumps.

(2) Open path subsystem

A fast-response CO$_2$ density open-path infrared gas analyzer (LI-7500; Li-Cor) was mounted on 2-m tower and sampled at 10 Hz on data-logger. The infrared gas analyzer was calibrated as outlined in the Li7500 instruction Manual (LI-COR, Inc., 2000). In order to ensure that the system work correctly, open-path infrared gas analyzer was used to calibrate the close-path infrared in the field. In addition, the open-path analyzer can be used instead of close-path analyzer when the close-path analyzer will be malfunction by placing a tube into LI-7500 sensor head with inlet and outlet port and connect it to the main port of the system.

(3) Soil chamber subsystem

The open-flow IRGA method (OF-method) is a valid and reproducible method for the determination of CO$_2$ evolution from the soil (Nakadai et al., 1993). The soil chamber described in this study is based on the principles of the OF-method (Mariko et al., 2000). The CO$_2$ flux chamber is an open system with an area of 339.6 cm$^2$ and volume of 1698.1 cm$^3$ (Fig. 3). The bottom of the chamber, 20.8 cm in diameter and 26 cm in height with an open bottom end, was pushed into the soil. The chamber was placed between the 6-m air intake and the corresponding solenoid valve. Two flow meters (FD-A10, Keyence) with needle valves were used to measure and control the flow rate of air entering the chamber was controlled by flow meter with needle valve, which was located between the diaphragm pump and the chamber. The diaphragm pump was placed between the 6-m air intake flow meter and the chamber. The outlet tube of the chamber was connected to first air intake port of profile system. The outgoing air from the chamber was pushed by a sampling pump in the profile system into the infrared gas analyzer with the constant flow rate.
of 1 L min⁻¹. The flow rate (1 L min⁻¹) of outgoing air from the chamber was controlled by a flow meter with a needle valve, which was located between the chamber and the infrared gas analyzer in the profile system. The same sampling pump and flow meter with a needle valve in the profile system was used for sampling air from the soil chamber. The air was exhausted from the soil chamber at a flow rate of 1.5 L min⁻¹. The fan was used to mix the air inside the chamber. Therefore, the air flow, consequently, into (2.5 L min⁻¹) and from (air sampled at 1 L min⁻¹ and exhausted at 1.5 L min⁻¹) the chamber was adequately controlled. This technique could equilibrate the air pressure outside and inside of the chamber. Temperature in the chamber was measured by using a copper-constantan thermocouple probe, which was connected to a data-logger.

(4) Associated environmental measurements
Air temperature profiles were measured using multisensor copper-constantan thermocouple probes. The thermocouples were set near the air inlet at six heights along the tower and shaded to avoid direct sunlight. Photosynthetic photon flux density was measured using quantum sensors (190SB, Li-Cor) at the top of the tower. All sensors were connected to the data-logger (DA-100, Yokogawa) and measured every 10s for each monitoring height.

(5) Ethernet/LAN data acquisition subsystem
The data acquisition system (DA-100, Yokogawa) with macros was designed to acquire instantaneous real-time measurement data automatically from the remote field to the desk top PC in a laboratory at 10s sample intervals. A large volume of data extensively measured by different instrumentations was transmitted directly from the data logger to Microsoft Excel spreadsheets via the Ethernet/LAN interface. The add-in Excel macro program on Microsoft Excel spreadsheets was developed to convert digital data to scientific units; separate data for each level according to the mode of solenoid valves, and the meteorological data were stored every 10s for each level.

(6) Calculation of CO₂ storage flux
The CO₂ storage flux was calculated by integrating the change in CO₂ concentration, c, through the air column as a function of height (z) for every 30 min (Baldocchi et al., 1997):

\[ F_{\text{storage}} = \sum \frac{\Delta c(z)}{\Delta t} \Delta z \]

where \( z \) is the measurement height and \( \Delta c/\Delta t \) refers to the temporal change in CO₂ concentration over a 30-min period, and \( \Delta z \) is the height of the layer. The sign convention used in this study was that negative values indicate CO₂ (or carbon) removal from the atmosphere, while a positive value marks CO₂ (or carbon) loss from the ecosystem (Haszpra et al., 2005).

Results and Discussion
1. The performance of the system
This system can produce a high-resolution gradient at a low cost, and has a light-weight and portable design. The fast air sampling technique and reduced time lag between levels enables a fast analyzer response. In contrast to the LI-6251 gas analyzer used by Miyata et al. (2000), the infrared gas analyzer (LI-840, Li-Cor) can measure both CO₂ and H₂O at a low cost. The LI-6251 needs a condenser for reducing moisture content while LI-840 does not because it has a water filter. For the measurement of vertical gradients, a single infrared gas analyzer was used for all levels to minimize variations between instruments. The instrumentations of the apparatus were fitted and placed in one box with a weight of about 10 kg. The box can be carried and moved from one site to another. It is easy to connect the inlet tubes of the tower to the sampling ports of the apparatus.

In contrast to other data-loggers, the data-logger (DA100, Yokogawa) can be easily and flexibly configured using a PC as a human interface and expanded to meet a wide range of applications. The data-logger units are compact and light-weight. It is a stand-alone
model, which has two subunits, DS400 and DS600. This data-logger has a width of 422 mm, height of 176 mm, and weight of approximately 0.8 kg. It is an inexpensive system for compactly configuring a data acquisition environment for remote measurements.

2. The time response of the system

The micrometeorological elements fluctuate in a very short time. These fluctuations affect the distribution and diffusion of CO₂ and H₂O. The fluctuations of CO₂ and H₂O should be measured as quickly as possible. The data then can be averaged in 15 min or 30 min. For example, the use of the averaging time of 5 min for the measurements of CO₂ and H₂O flux with Bowen ratio/balance apparatus provided good data of CO₂ and H₂O flux (Steduto and Hsiao, 1998). In addition, such instantaneous CO₂ profiles are frequently accompanied by large noise under calm conditions because of a gust (Hirano et al., 2007). The CO₂ storage fluxes from instantaneous CO₂ profiles are calculated at 5 min intervals and averaged storage flux hourly to remove the noise. Therefore, the gradient systems should have a rapid response time for measuring the sampled air as quickly as possible. A laboratory test was conducted to investigate the delay time, which was needed to allow the system to reach a steady-state. The delay time was measured by switching from a different known standard concentration of CO₂ at a constant flow rate of 1 L min⁻¹. The lower plateau represents the measurements of zero μmol mol⁻¹ CO₂ in air (Fig. 4). While the upper plateau represents the measurements of 400 μmol mol⁻¹ CO₂ in air. Air was pumped through the system every 10s and 20s. A delay time of about 4s was found after switching the solenoid valve before the infrared gas analyzer measured the actual change in CO₂ concentration. The best time at which the system was in the best steady-state, was found to be 10s. Therefore, the CO₂ data in this system was recorded every 10s for each measurement level: 4s were needed to wash the sample pump and the infrared gas analyzer cell from the air from the previous sampling air, and 6s were needed to allow the system to reach the steady-state. When the steady-state of the system was completely reached, one reading of the infrared gas analyzer was recorded and stored on the Spreadsheet of Microsoft Excel.

3. The differences from other previously developed system

A multiple-pump system for minimizing the lag time of air purge has already been developed (Xu et al., 1999). However, there was a difference between the pump system used in the system presented here and the pump system in previously developed systems. For example, Xu et al. (1999) used only one large purge pump for sucking air from the five heights without measurement. However, two purge pumps were used in this study for simultaneously sucking air from all levels of measurements. Air from all tubes of all levels will be available in each solenoid valve. The flow rate of exhausted air from these two purge pumps was approximately 8 L min⁻¹. Therefore, this apparatus can measure quickly the change in CO₂ and H₂O concentration over a short period of time. The system presented here measured the values at six different heights at as short as 1 min per cycle. This is very short compared with other system. For example, the formerly developed gradient system took about 10 min (Buchmann and Ehleringer, 1998; Brooks et al., 1997), 20 min (Ahonen et al., 1997) and 30 min (Leuning et al., 2000; Miyata et al., 2000) for one cycle.

4. Excel macro for data processing

Typical meteorological software for data processing is very difficult to manipulate and use because a high programming level is needed. The concomitant use of Excel macro programs for routine meteorological analysis can be significantly time-saving. Furthermore, the software comes with most computers, is easy to use, low cost, and offers charting facilities. Microsoft Excel has a limited function for gradient systems without the new macro program. For this reason, Excel macros have been recently developed for importing digital data from all instrumentations and converting them to scientific units. Data were separated for a given level of measurement based on the solenoid valves to another spreadsheet. One spreadsheet contained 1 min data of one level. Then, 1 min per sampling cycle of data of each measurement level were averaged over 30 min time intervals.

5. Evaluation of the system

This system has been tested at different study sites for over one year at agricultural fields such as sugarcane and sorghum fields. Data for sorghum and sugarcane are shown in Figs. 5 and 6, respectively. The weather condition in Okinawa, where the study sites were located, is unstable throughout the day and year. This unstable condition causes high fluctuations in micro-environmental elements within and above the canopy of plants. Therefore, fluctuations in CO₂ and H₂O concentration, and air temperature were observed within and above the canopy of sorghum and sugarcane (Figs. 5, 6). These fluctuations were highest near the soil surface and decreased with increasing heights. The characteristics of these fluctuations within the canopy of sorghum differed from those within the canopy of sugarcane. Therefore, these results indicate that the plant canopy appears to affect its own micro-environmental elements. These effects differed with the plant species. The plant canopy appears to self-generate its own environment completely different from those the canopy. The high CO₂ concentrations near the soil surface and below the canopy probably
might be due to the low quantity of photosynthetic organs, low light intensity, and high net respiration and biological activities. However, the low CO₂ concentration within the mid-canopy layer during midday may be due to the high photosynthetic organs, which consume a large quantity of CO₂ (Murayama et al., 2003). There were diurnal variations in CO₂ and H₂O concentrations and air temperature within and above the canopy of sugarcane and sorghum. The CO₂ concentration decreased from 0700 to 1200. This was perhaps because the increased photosynthetic photon flux density increased the photosynthetic activity. Therefore, the CO₂ accumulated and stored within the canopy during the nighttime might be consumed by photosynthesis during the daytime. These CO₂ concentrations stored during the nighttime might be emitted by respiring soil and biological activities.

6. Soil chamber method
The soil chamber apparatus coupled with a gradient system was designed to examine the source of CO₂ near the ground level. The data of soil CO₂
concentration was obtained from the absolute measurements of air exiting the chamber (Fig. 6). The trend of CO$_2$ concentration of air going out of the chamber was almost similar to the trend of CO$_2$ concentration near the soil surface measured with the gradient system. The CO$_2$ concentration near the soil surface and that of air going out of the chamber, their peaks occur approximately around 0300. This might indicate the concentration of CO$_2$ from the soil surface. There should be a positive relationship between the soil respiration and air temperature. However, there was an unusual relationship between the dynamics of CO$_2$ and air temperature inside the chamber (Fig. 6). This might be because the temperature of the enclosure affected the air temperature inside the chamber. This effect might be due to the heat difference between outside and inside the chamber, which cause the heat flux from the enclosure to the environment of the chamber, and vice versa. Furthermore, the thermocouple temperature...
probe is exposed to direct sunlight during the daytime. In addition, direct radiance during the daytime might increase the air temperature inside the chamber.

During a calm night when there is a low turbulent intensity, a large amount of CO₂ usually accumulates near the soil surface. One most likely source of CO₂ is the soil. We designed the soil chamber to separate the soil CO₂ from other sources. This OF-method has adequate technical requirements ensuring that no contamination occurs between the ambient air and the air inside the chamber. The air pressure inside the chamber may be higher than that outside the chamber. This may be because two sampling pumps were used to suck the air. The first pump and flow meter were placed between the soil chamber and the infrared gas analyzer that were used to push the sampled air from the chamber to the infrared gas analyzer for the measurement with the constant flow rate of 1 L min⁻¹. The exceeding air inside the air chamber was evacuated through the exhaust spaces.

7. The examples of data measured by the system

(1) Vertical profiles of CO₂ within the canopy

The lowest CO₂ concentration was observed in the mid-canopy of sorghum at midday. There were differences between sugarcane and sorghum in the characteristics of vertical profiles of CO₂ (Fig. 7). Although the CO₂ concentration near the soil surface was higher in the sorghum field, the CO₂ concentration at 2 m above ground was higher in the sugarcane field. The shape of the vertical CO₂ profile in the sugarcane field showed a diurnal change while that in the sorghum field remained relatively unchanged. The storage CO₂ flux in the sugarcane field had more negative values than that in the sorghum field (Fig. 8). This might mean that the sugarcane field stored a large amount of CO₂ in the air layer between 0 and 6 m height than that in the sorghum field. This phenomenon might be due to the difference between the sorghum field and sugarcane field in inter and intra row spacing and canopy heights.

(2) Standard deviation

To determine the standard deviation at different average time scales, we averaged the data in the sugarcane field at 0 and 6 m levels for 10, 30 and 60 min (Fig. 9). At the 0 m level, the mean standard deviation was 8.9, 9.7 and 11 μmol mol⁻¹ in the 10, 30 and 60 min-average time scale, respectively. However, at the 6 m level, the mean standard deviation was 1.4, 1.8, and 2.9 μmol mol⁻¹ in the 10, 30 and 60 min-average time scale, respectively. The mean standard deviation of all averaging periods at the 0 m level was higher than that at the 6 m level. The large variation near the ground level might be because the CO₂ respired in the soil. At the 0 and 6 m level, the standard deviation of the mean can be reduced by measuring a large number of samples.

(3) Storage flux of CO₂ within the canopy

The meteorological methods e.g. eddy covariance method are powerful tools to determine the net ecosystem exchange. However, the eddy covariance method focuses on the sampling at one height only above the plant canopy. For the measurement of net ecosystem exchange, it is very important to calculate accurate rate of change of CO₂ storage (Iwata et al., 2005). The CO₂ storage flux depends on the measurement of CO₂ concentration profile in the air layer below the flux measuring height of eddy
covariance. The technique described here can be coupled with the eddy covariance method to measure the net ecosystem exchange. The net ecosystem exchange can be mathematically calculated as the sum of eddy flux above the canopy and the rate of change of CO₂ storage below the eddy covariance level.

(4) Other implications of the system
This system can be easily implicated to estimate scalar fluxes, e.g. CO₂ or H₂O flux or evapotranspiration by using surface renewal analysis method (Paw et al., 1995). The system has characteristics that can provide much of the required associated micro-environmental data with the same time interval. For example, a sensor for the photosynthetic photon flux density can be connected to the system. Sample data of photosynthetic photon flux density showed that light intensity was unstable and fluctuated with time (Fig.10).

8. The problem of the limited fetch environment
The aerodynamic boundary layer was attained with the height-to-fetch ratio of 1:5. The fetch was 10 and 8.4 m in the sugarcane and sorghum field, respectively. Thus the measurement height of 6 m in the sugarcane field and 3, 4 and 6 m in the sorghum field were outside the boundary layer. This may indicate that the air layer at 6 m in the sugarcane field and at 3, 4 and 6 m in the sorghum field might be affected by the surrounding agricultural crops. The difficulty in assessing the effective fetch length due to the limited fetch environment at agricultural fields may affect the validity of the results. Hence, in order to reduce the effect of limited fetch, the measurement height should be located within the plant canopy.

Fig. 8. CO₂ storage flux of sorghum (solid-square) and sugarcane (open-circle) crop. The data were measured every 10 s for each monitoring level with a total of 1 min per sampling cycle and averaged for 30 min. In the sorghum field, the measurements were conducted during the period from 1800 on 24 to 1800 on 25, August 2006. In the sugarcane field, the measurements were conducted during the period from 1800 on 17 to 1800 on 18, October 2006.

Fig. 9. The standard deviations of diurnal variations in CO₂ concentration in the sugarcane field. The data were measured every 10 s for each monitoring level and averaged for 10, 30 and 60 min. The data were collected at the 0 and 6 m level. In the sorghum field, the measurements were carried out during the period from 1800 on 24 to 1800 on 25, August 2006. In the sugarcane field, the measurements were carried out during the period from 1800 on 17 to 1800 on 18, October 2006.
Conclusion

This system is ideal for measuring CO$_2$, H$_2$O and associated micro-environmental parameters at different study sites such as agricultural fields (e.g. sorghum and sugarcane crops) and forests (e.g. mangrove forest). Furthermore, this system has potential for use in measurement of CO$_2$, H$_2$O micro-environmental elements, CO$_2$ storage flux, and other processes including CO$_2$ sink and source.

References

Ahonen, T., Aalto, P., Rannik, Ü., Kulmala, M., Nilsson, E.D., Palmroth, S., Ylitalo, H. and Hari, P. 1997. Variations and vertical profiles of trace gas and aerosol concentration and CO$_2$ exchange in eastern Lapland. Atmos. Environ. 31 : 3351-3362.

Baldocchi, D.D., Vogel, C.A. and Hall, B. 1997. Seasonal variation of carbon dioxide exchange rates above and below a boreal jack pine forest. Agric. Forest Meteorol. 83 : 147-170.

Bazzaz, F.A. and Williams, W.E. 1991. Atmospheric CO$_2$ concentration within a mixed forest: Implications for seedling growth. Ecology 72 : 12-16.

Brooks, J.R., Flanagan, L.B., Verney, G.T. and Ehleringer, J.R. 1997. Vertical gradients in photosynthetic gas exchange characteristics and refixation of respired CO$_2$ within boreal forest canopies. Tree Physiol. 17 : 1-12.

Buchmann, N. and Ehleringer, J. 1998. CO$_2$ concentration profiles, and carbon and oxygen isotopes in C$_3$ and C$_4$ crop canopies. Agric. Forest Meteorol. 89 : 45-58.

Chunlin, W., Guoyi, Z., Xu, W., Xuli, T., Chuanyan, Z. and Guirui, Y. 2007. Below-canopy CO$_2$ flux and its environmental response characteristics in a coniferous and broad-leaved mixed forest in Dinghushan, China. Acta Ecologica Sinica 27 : 848-854.

Ehleringer, J. and Cook, C.S. 1980. Measurements of photosynthesis in the field: utility of CO$_2$ depletion technique. Plant Cell Environ. 3 : 479-482.

Grace, J., Lloyd, J. and McIntyre, J. 1995. Fluxes of carbon dioxide and water vapor over an undisturbed tropical forest in south-west Amazonia. Global Change Biol. 1 : 1-12.

Goulden, M.L., Munger, J.W., Fan, S.M., Daube, B.C. and Wofsy, S.C. 1996. Measurements of carbon sequestration by long-term eddy covariance: methods and a critical evaluation of accuracy. Global Change Biol. 2 : 169-182.

Gu, L., Falge, E.M., Boden, T., Baldocchi, D.D., Black, T.A., Saleska, S.R., Suni, T., Verm, S.B., Vesala, T., Wofsy, S.C. and Xu, L. 2005. Objective threshold determination for nighttime eddy flux filtering. Agric. Forest Meteorol. 128 : 179-197.

Haszpüra, L., Barcza, Z., Davis, K.J. and Tarczay, K. 2005. Long-term tall tower carbon dioxide monitoring over an area of mixed vegetation. Agric. Forest Meteorol. 132 : 58-77.

Hirano, T., Segah, H., Harada, T., Limin, S., June, T., Hirata, R. and Osaki, M. 2007. Carbon dioxide balance of a tropical swamp forest in Kalimantan, Indonesia. Global Change Biol. 13 : 412-425.

Hollinger, D.Y. and Richardson, A.D. 2005. Uncertainty in eddy covariance measurements and its application to physiological models. Tree Physiol. 25 : 873-885.

Iwata, H., Malhi, Y. and von Randow, C. 2005. Gap-filling measurements of carbon dioxide storage in tropical rainforest canopy airspace. Agric. Forest Meteorol. 132 : 305-314.

Kumagai, T., Kuraji, K., Noguchi, H., Tanaka, Y., Tanaka, K. and Suzuki, M. 2001. Vertical profiles of environmental factors within tropical rainforest, Lambir National Park, Sarawak, Malaysia. J. For. Res. 6 : 257-264.

Leuning, R., Denmead, O.T., Miyata, A. and Kim, J. 2000. Source/sink distribution of heat, water vapour, carbon dioxide and methane in a rice canopy estimated using Lagrangian dispersion analysis. Agric. Forest Meteorol. 104 : 233-249.

LI-COR, Inc. 2000. LI-7500 CO$_2$/H$_2$O Analyzer Instruction Manual. LI-COR Inc., Lincoln, Nebraska.

Marioko, S., Nishimura, N., Mo, W., Matsui, Y., Kibe, T. and Koizumi, H. 2000. Winter CO$_2$ flux from soil and snow surface in a cool temperature deciduous forest. Jpn. Ecol. Res. 15 : 363-372.

Maitani, T. and Seo, T. 1986. A case study of temperature fluctuations within and above a wheat field before and after sunset. Boundary Layer Meteorol. 35 : 247-256.

Miyata, A., Leuning, R., Denmead, O.T., Kim, J. and Harazono, Y. 2000. Carbon dioxide and methane fluxes from an intermittently flooded paddy field. Agric. Forest Meteorol.
102 : 287-303.
Murata, Y. 1981. Dependence of potential productivity and efficiency for solar energy utilization on leaf photosynthetic capacity in crop species. Jpn. J. Crop Sci. 50 : 223-232.
Murayama, S., Yamamoto, S., Saigusa, N., Kondo, H. and Takamura, C. 2005. Statistical analysis of inter-annual variations in the vertical profile of atmospheric CO₂ mixing ratio and carbon budget in cool-temperate deciduous forest in Japan. Agric. and Forest Meteorol. 134 : 17-26.
Nakadai, T., Koizumi, H., Usami, Y., Satoh, M. and Oikawa, T. 1993. Examination of the method for measuring soil respiration in cultivated land: effect of carbon dioxide concentration on soil respiration. Ecol. Res. 8 : 65-71.
Paw, K.T., Qui, J., Su, H., Watanabe, T. and Brunet, Y. 1995. Surface renewal analysis: a new method to obtain scalar fluxes. Agric. Forest Meteorol. 74 : 119-137.
Rasse, D.P., Stolaki, S., Peresta, G. and Drake, B. 2002. Pattern of canopy-air CO₂ concentration in a brackish wetland: analysis of a decade of measurements and the simulated effects on the vegetation. Agric. Forest Meteorol. 114 : 59-73.
Ruimy, A., Jarvis, P.G., Baldocchi, D.D. and Saugier, B. 1995. CO₂ Fluxes over plant canopies and solar radiation: a literature review. Adv. Ecol. Res. 26 : 1-68.
Steduto, P. and Hsiao, T.C. 1998. Maize canopies under two soil water regimes IV. validity of Bowen ratio-energy balance technique for measuring water vapor and carbon dioxide fluxes at 5-min intervals. Agric. Forest Meteorol. 89 : 215-228.
Wilson, K.B. and Meyers, T.P. 2001. The spatial variability of energy and carbon fluxes at the floor of a deciduous forest. Boundary Layer Meteorol. 98 : 443-473.
Xu, L.K., Matista, A.A. and Hsiao, T.C. 1999. A technique for measuring CO₂ and water vapor profiles within and above plant canopies over short periods. Agric. Forest Meteorol. 94 : 1-12.