2.4 CO₂ storage change

Net Ecosystem CO₂ Exchange (NEE) is generally expressed as the sum of the CO₂ flux observed over the vegetation surface and the observed CO₂ storage change that takes place over time in the space between the ground surface and the flux measurement height:

NEE =
$$F_c + F_s = \overline{w' \rho_c'} + \int_0^{z_f} \frac{\overline{\partial \rho_c}}{\partial t} dz$$
 (2.4-1)

Where, F_c : CO₂ flux at the measurement height [mgm⁻²s⁻¹], F_s : CO₂ storage change [mg m⁻²s⁻¹], w: vertical wind velocity [ms⁻¹], ρ_c : CO₂ concentration [mgm⁻³], t: time [s], t: height [m], t: flux measurement height [m], ': fluctuating component and : mean value.

The value of the CO₂ storage change is small over short plant canopies such as crops. However, over tall plant canopies such as forests, the value of the CO₂ storage change becomes sufficiently large with respect to the value of CO₂ flux that the CO₂ storage change cannot be neglected (Baldocchi *et al.*, 2001). Particularly for several hours after sunrise, the value of CO₂ storage change sometimes becomes as large as or larger than that of the flux. According to Baldocchi *et al.* (2000), the value of the daily CO₂ storage change (total over 24 hours) becomes close to zero, thus can be neglected for evaluating NEE. However, evaluations of CO₂ storage change are required for evaluations of NEE on the time scale of 30 to 60 minutes.

Tips!

In Equation 2.4-1, the horizontal/vertical advection and horizontal turbulence flux terms are neglected. As a result, NEE is expressed only in terms of the vertical turbulence fluxes and storage change. Due to technical constraints, flux observations at the present time usually neglect the horizontal transport terms by assuming "horizontal homogeneity". Furthermore, because the vertical advection term is difficult to estimate, it is not included in the evaluation of NEE in most cases. Accordingly, it is important to select a site that matches the assumptions in Equation 2.4-1 as closely as possible.

A study on the vertical advection term has been conducted by Lee (1998). In recent years, attempts have been made to evaluate the horizontal/vertical advection terms on the basis of observations (Aubinet *et al.*, 2003; Aubinet *et al.*, 2005; Leuning *et al.*, 2008).

Tips 2.4-1

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Measuring procedures

CO₂ storage change is evaluated from the temporal change of the atmospheric CO₂ concentration in the air below the flux measurement height. Because the vertical distribution of CO₂ concentration in the

vegetation layer is not uniform, CO₂ concentration must be measured at multiple heights.

When a single closed-path gas analyzer is used, two measurement techniques can be used for evaluating CO₂ storage change: 1) CO₂ concentration can be measured sequentially at each measurement height. In this technique, air is sampled through inlets at multiple heights by switching flow pathways with the use of pumps and solenoid valves; and 2) CO₂ concentration of a mixture of air sampled from multiple measurement heights is measured. An advantage of the former method is that it provides information on the CO₂ concentration at individual measurement heights. Disadvantages of the former method include a somewhat complex controlling system for switching the flow paths as well as a prolonged time interval between measurements. Although these disadvantages can be eliminated by the use of multiple CO₂ analyzers, frequent calibration is required to correct for errors that arise from variations among instruments.

Determination of measuring points/ the number of measuring points

It is desirable to measure CO₂ concentration at as many heights as possible so that the spatially-averaged value of CO₂ concentration can be evaluated. However, when CO₂ concentration is measured sequentially at each measurement height, the measurement interval (the period between measurements) at a particular measurement height becomes larger with an increasing number of measurement points. These factors need to be taken into account when determining the number of measurement points.

CO₂ concentration varies significantly near the soil surface and near leaves (or forest canopy in the case of a forest). Therefore, the heights and number of measurement locations need to be determined appropriately by taking into account the structure of the plant canopy of interest. The effects of the heights and number of measurement locations on the evaluated values of the CO₂ storage change are discussed in Yang *et al.* (1999) and Yang *et al.* (2007).

Measurement system

Fig. 2.4-1 illustrates an example of a measurement system which measures and records CO₂ concentration by sequentially sampling air at multiple measurement heights with a closed-path gas analyzer. In this example, the number of pumps used in the system is the same as the number of measurement heights.

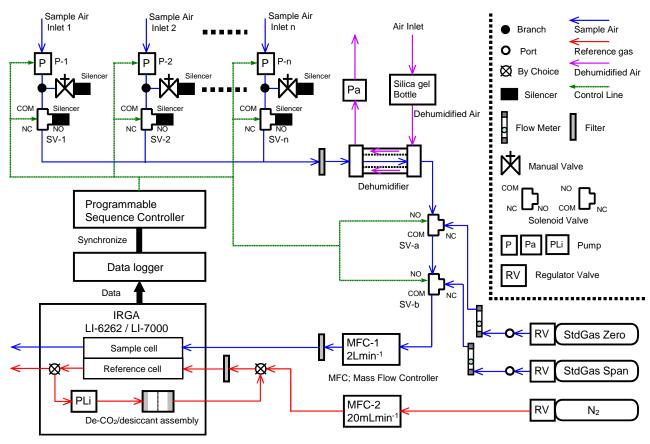


Fig. 2.4-1 A sample system for measuring CO₂ concentration profiles.

The piping in the system can be classified into the following three flow paths:

- 1. Flow path for supplying sampled air and calibration gas to the sample cell of the CO₂ analyzer (blue path in Fig. 2.4-1)
 - · Main flow path: sampled air
 - Merging flow path: calibration gas (zero and span gases)
- 2. Flow path for supplying reference gas to the reference cell of the CO₂ analyzer (red path in Fig. 2.4-1)
- 3. Flow path for supplying dry air for dehumidification (purple path in Fig. 2.4-1)

The system itself and cautions regarding its use will be explained by following the flow path for the sampled air and calibration gases in Fig. 2.4-1 (blue path).

Inlets for sampled air

- Fix the end of the tubing so that it points downward to prevent rain droplets from entering (refer to Tips 2.4-2 and photos $2.4-1 \sim 2.4-3$).
- Take appropriate measures to avoid taking in rain droplets, dust, and insects.

Suction tubing (piping)

- For outdoor piping, weather-proof tubing such as that made of PTFE (often marketed as "Teflon") should be used
- Flexible tubing (e.g., tubing made of polyurethane) is easy to handle in small spaces within the system.

Pumps

- Negative pressure occurs in the flow path upstream of the pump while positive pressure occurs in the flow path downstream of the pump.
- Caution is necessary to prevent leakage along the flow path under negative pressure.
- Caution is necessary to ensure that joints and other parts along the pressurized (positive pressure) flow can withstand the expected maximum pressure.

Manual valves

- A high suction flow rate of air is desirable to shorten the travel time of the air between the air inlet and the sample cell. Excess air should be vented before solenoid valves in order to reduce the pressure to a value less than the maximum allowable pressure of the solenoid valves and the sample cell, reduce the load on the pumps, and prevent dew formation in the mass flow controller.
- The flow rate can be controlled with manual valves.
- When setting up the system, use a flow meter to decide how far to open each valve. During this step, the
 flow rate of the air after the manual valves should be adjusted to a value close to that set by the mass flow
 controller.
- Caution is necessary to avoid opening the manual valves too much, as this will cause an insufficient flow rate.
- The valves should be disassembled and cleaned once a year.
- If silencers are added to the exhaust outlets, the silencers should be replaced periodically (approximately once a year) so that clogging of the silencers does not reduce the flow rate of excess air discharge.



Solenoid valves (switching between air samples from various measurement heights) SV-1, SV-2 ... SV-n

- Solenoid valves are used for switching between air samples from various measurement heights.
- Prior to opening a solenoid valve, it is recommended that air be drawn in up to the location of the solenoid valve (remove the stagnated air in the tubing between the air inlet and the solenoid valve) in order to shorten the time delay in the measurement due to the distance between the air inlet and the sample cell. For this purpose, create branched tubing between the pump and the solenoid valve for ventilating the excess air. Air is ventilated out of the branched tubing until the solenoid valve is opened.
- The investigator should be aware of the operational lifetime of the solenoid valves.
- Details of solenoid valves can be found in Section 2.3 "Closed-path CO₂ gas analyzers: (2) Solenoid valves".



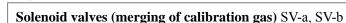
Air filters should be included in order to avoid problems caused by dust and dirt accumulating in the flow path.

- · Moderately priced air filters should be selected for use as the filters need to be replaced frequently.
- · Air filters should be replaced once every two to four weeks, depending on the amount of pollution in the air.
- Caution is necessary in selecting both the number of filters to be used and the pore diameters of the filters since these factors can increase the load on the pump.



• When only CO₂ concentration is measured, it is recommended that moisture in the sampled air be removed in order to prevent problems caused by dew formation in the measurement system.

- Purge gas (dry air) that is supplied into the dehumidifiers should be prepared with the use of silica gel or heatless dehumidifiers. (Refer to Section 2.3 "Closed-path CO₂ gas analyzers".)
- The investigator needs to ensure that the dehumidifier is firmly connected to the system tubing. Some dehumidifiers are prone to becoming disconnected from the system tubing.



- The reference gases for the CO₂ analyzer flow through the solenoid valves.
- Attach a pressure regulator to each reference gas cylinder.
 - Follow the operation manual for proper use of the regulator. Because the maximum allowable working pressure varies according to the pressure gauge attached to the regulator, select a pressure gauge with a full scale pressure range of 1.5 to 2 times the pressure to be applied. For example, consider a pressure regulator with an inlet (primary) pressure gauge and an outlet (secondary) pressure gauge. If the values of the maximum pressure at the inlet and the supply pressure at the outlet are assumed to be 15 Mpa and 0.1 MPa, respectively, select a regulator that has pressure gauges with full-scale ranges of approximately 25 MPa and 0.2 MPa.
 - Use a secondary pressure adjustment valve to reduce the pressure sufficiently to avoid applying an excessive load to the system.
 - The pressure range of the secondary pressure adjustment valve should be appropriate for the pressure-tightness of the piping downstream, so that improper opening/closing of this pressure adjustment valve will not impose an excessive load on the piping. Do not select a secondary pressure adjustment valve with high pressure-tightness for versatility.

Mass flow controllers

The flow rate should be set by taking into account the maximum allowable flow rate for the cells of the CO₂ analyzer.

Filters

· Gelman filters have directionality and must be installed accordingly.

Sample cells of the gas analyzer

• The investigator needs to confirm the maximum allowable inflow rate into and the maximum allowable pressure inside the sample cells by referring to the manual.

Ventilation from the gas analyzer

• When the flow rate is low, installation of an exhaust tube (suggested length: approximately 30 cm on an empirical basis) is required in order to avoid the influence of the outside air.

Tips!

A funnel and a tea strainer (Photo 2.4-1), a film canister (Photo 2.4-2) or a silencer (Photo 2.4-3) can be added to the air inlet. When a film canister is used, it is recommended that a small wad of synthetic cotton be placed inside the canister to prevent insects from entering.

Tips 2.4-2



Photo 2.4-1 Air inlet (funnel and tea strainer).



Photo 2.4-2 Air inlet (film canister).



Photo 2.4-3 Air inlet (silencer).

It is suggested that the investigator refer to the above-mentioned cautions for the path marked in red as well as the path marked in blue.

(1) Control system method

The system controls the following two components:

- 1. Sample air intake at individual measurement heights: control of the pumps and solenoid valves (turning on/off of P-1 ~ P-n and SV-1 ~ SV-n in Fig. 2.4-1)
- 2. Calibration gas: control of solenoid valves (turning on/off of SV-a and SV-b)

An example of the control for the sample air intake is shown in Fig. 2.4-2. In this example, the pump at the height of the next measurement is "turned on" in advance so that the relevant sample air is drawn to the location immediately ahead of the analyzer. This technique minimizes the delay in the arrival time of the sample air of interest at the time of switching measurement points.

```
hh: mi ( P1, SV1, P2, SV2, P3, SV3, P4, SV4, P5, SV5, SVa, SVb)
hh: mi (0, 0, 0, 0, 0, 0, 0, 0, 0, 0)
(0/1: off/on) Pn(n=1~5) pump; SVn (n=1~5, a, b) solenoid valve
   Standard switching of the measurement points for sample air intake (5 heights)
hh: mi ( P1, SV1, P2, SV2, P3, SV3, P4, SV4, P5, SV5, SVa, SVb)
           1,
hh: 00(1,
                1,
                   0,
                       0,
                           Ο,
                               0,
                                   0,
                                       0,
                                           0,
                                              0, 0) Sample 1 taken in
hh: 02( 0,
                1,
                       1,
            0,
                    1,
                           0,
                               0,
                                   0,
                                       0,
                                           0,
                                               Ο,
                                                  0) Sample 2 taken in
hh: 04(0,
            0,
                Ο,
                   0,
                       1,
                           1,
                               1,
                                   0,
                                       0,
                                           0,
                                               0, 0) Sample 3 taken in
hh: 06(0,
                0,
                   0,
                       0,
                           0,
            0,
                               1,
                                   1,
                                       1,
                                           0,
                                               0, 0) Sample 4 taken in
hh: 08( 1,
            0,
                Ο,
                   0,
                       0,
                           0,
                               0,
                                   0,
                                       1,
                                           1,
                                               0,
                                                 0) Sample 5 taken in
hh: 10( 1,
                1,
                   0,
                       0,
                           0,
                               0,
                                   0,
                                       0,
                                           0,
                                               0,
                                                  0) Sample 1 taken in
            1,
hh: 12( 0,
            0,
                1,
                    1,
                       1,
                           0,
                               0,
                                   0,
                                       0,
                                           0,
                                               0,
                                                   0) Sample 2 taken in
· Zero gas calibration
hh: mi ( 0, 0, 0, 0, 0,
                           0, 0,
                                   0,
                                       0, 0,
                                                   0)
   Span gas calibration
hh: mi ( 0, 0, 0, 0, 0, 0, 0,
                                   0, 0, 0, 0,
                                                   1)
```

Fig 2.4-2 An example of a control system for the sampling system shown in Fig. 2.4-1. (Number of measurement points: 5, frequency of measurement height switchover: every 2 min., time required for a single measurement cycle of the entire profile: 10 min.)

It is recommended that the system for measuring the CO₂ concentration profile be built so that both automatic and manual control of the system are possible. Such a system allows ease of maintenance and response to abnormalities.

When a data logger with an output port (e.g., CR1000, Campbell Scientific, Inc., US) is used, the output values from the CO₂ analyzer can be recorded simultaneously with the switchover of the measurement heights. In this case, mis-synchronization between the time on the data logger and the time of the measurement height switchover can be eliminated. When the system for the measurement height switchover is not linked to the data logger, the voltage of the solenoid valve and the output values from the CO₂ analyzer should both be recorded in order to identify the actual measurement height at which CO₂ concentration was measured.

(2) Examples of other types of systems

The measuring system described above uses the same number of pumps for drawing in sample air as the number of measurement heights. The vertical profile of CO₂ concentration can also be measured by a single pump if it is installed downstream of the location at which flow path switching takes place. However, in this set up, air cannot be drawn in from the next height for measurement in advance. As a result, at the time of the sampling height switchover, the measurement delay will be larger than that in the system described in (1) Control system method. Given this background, Xu et al. (1999) created a system that uses two pumps for high-speed sampling of concentration profiles. Furthermore, Ohtani et al. (2005) proposed a system that specializes in the measurement of CO₂ storage changes and does not measure concentration profiles. This system takes in air samples simultaneously at six measurement heights within a forest canopy. The average CO₂ concentration of the forest canopy is evaluated by mixing the air samples from the six measurement heights. The proportion of sampled air added to the air mixture from each measurement height depends on the thickness of the air layer that is represented by the measurement height. The CO₂ storage change within the forest canopy is calculated from the temporal change in the evaluated value of the average CO₂ concentration of the forest canopy.

In summary, as these examples show, various types of measuring systems can be designed.

Calculation method

Theoretically, the CO₂ storage change is evaluated from the difference between the instantaneous CO₂ concentration at the beginning of the flux averaging period and that at the end of the flux averaging period. However, this method yields calculation results that differ significantly from the true concentration change of interest (Finnigan, 2006). Although the CO₂ storage change is sometimes evaluated from the difference in the 30-minute average values of CO₂ concentration, this approach underestimates the values that are sought (Finnigan, 2006). Baldocchi *et al.* (2000) calculated the CO₂ storage change from the temporal change of the CO₂ concentration profile (four measurement heights) that was obtained from data collected every 120 seconds.

Because measurements of CO₂ concentration profiles do not provide accurate CO₂ concentration profiles

at the beginning and the end of the flux averaging period, Yang *et al.* (2007) calculated the CO₂ storage change by applying a spline interpolation to the measurement values from the measurement heights. In this method, 3-minute average values at the beginning and end of the flux averaging period are used in order to reduce random errors.

₹ Tips!

As shown above, the method for calculating the CO_2 storage change, F_s , varies among research groups, giving the impression that no standardized calculation method has yet been established. However, the following equation is used in every evaluation of the CO_2 storage change:

$$F_{\rm s} = \int_0^{z_{\rm f}} \frac{\overline{\partial \rho_{\rm c}}}{\partial t} dz = \sum_{\rm i=1}^n \frac{\Delta \rho_{\rm c_i}}{\Delta t_{\rm f}} \Delta z_{\rm i}$$

where Δt_{f} : flux averaging period, Δp_{c_i} : change in the CO₂ concentration of the air layer i over the flux averaging period, Δz_i : thickness of the air layer i, and n: the number of measurement heights.

Tip 2.4-3