Measurement of CO₂ Flux in Plant Communities

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Abstract.

A review of several CO₂ flux measuring techniques for plant communities is briefly presented. The development of fast response CO₂ sensors, an international comparison of them, and some results obtained using them are described in this paper. After alternate investigations of the different measuring techniques, it was found that they should be used to supply representative information of CO₂ fluxes under various environmental and physiological conditions.

Key words. CO₂ flux, measuring techniques, eddy correlation method, plant communities, CO₂ fluctuation sensor

1. Introduction

Plants grow using environmental resources and in response to the environment. The exchange of CO₂ and numerous trace gases such as CH₄, N₂O and NO_x between the biosphere influences the composition and the global climate. Especially, the exchange of CO₂ between the biosphere and atmosphere is not only important to study dry-matter production of field crops but also to predict future atmospheric concentration. Numerous techniques for measuring and recording CO₂ flux between plant communities and the atmosphere have been developed over the past 40 years.

The development of CO₂ flux measuring techniques for plant communities, especially the eddy correlation method, is reviewed briefly at first. Nextly some examples of the results of recent field experiments using the eddy correlation method are presented. We will also consider the possibilities of development of current measuring techniques of CO₂ flux and their application in future measurement programs.

2. Review of the development of CO₂ flux measuring techniques in plant communities

Reviews of micrometeorological techniques for the measurement of CO₂ flux in plant communities under the natural environment have been carried out by many researchers (e.g. Thom, 1975; Rosenberg et al., 1983; Jarvis and Sandford, 1985; Desjardins and MacPherson, 1989; Fowler and Duyzer, 1989 and others). These techniques have an advantage that they do not give any disturbance to plants other than the installation of a mast to support the equipment. At first we will shortly review the aerodynamic and energy balance methods which have long been used to estimate CO₂ flux. Next we will review the eddy correlation method which became practical, especially over the last ten years. Finally we will describe an example of a trial of CO₂ budget method which is expected to become a promising method for the estimation of CO₂ flux of ecosystems.

2.1. The aerodynamic method

In principle, the flux of CO₂ above plant communities is estimated from the vertical gradient of gas concentrations and an appropriate transfer coefficient. This method was first applied to the measurement of CO₂ flux over growing crops by Huber (1950), using an infrared gas analyzer (URAS) developed in Germany. Inoue

et al. (1958) and Lemon (1960) used gradients to estimate the diurnal variation of CO_2 flux. From records of several weeks, Montieth and Szeicz (1960) obtained good agreement between meteorological estimates of CO_2 flux over a sugar beet field, and conventional estimates from dry-matter production. After 1960, many researchers have estimated the CO_2 flux in a wide range of conditions, applying stability corrections to eddy diffusivities (Baumgartner, 1969; Uchijima, et al., 1967). These estimates present useful information concerning CO_2 flux over plant communities. However, both the conceptual foundation of the K theory and the practical consequences of using it near sources and sinks have been widely questioned (Finnigan and Raupach, 1987).

2.2 Energy balance method (Bowen ratio method)

Another gradient technique is based on the energy balance at the ground, which is dependent on the partition of net absorbed radiation by the underlying surfaces, plant and soil. Assuming that the eddy diffusivity for carbon dioxide is the same as the coefficient for heat and water vapor, it is possible to estimate the flux of CO_2 . This method does not require wind velocity profile measurements. Therefore, it is generally believed that the energy balance method contains less error than the aerodynamic method, because it can avoid complications and uncertainty introduced by stability corrections. However, the greatest drawback is that the error in flux is directly proportional to the accuracy of the measurement of difference of net radiation and ground heat flux. It is difficult to get satisfactory CO_2 fluxes under too little available net radiation on cloudy days, nights or under winter conditions. Since Uchijima (1962) proposed this method for determining the turbulent transfer coefficient at given heights in a canopy, many researchers used it to estimate CO_2 fluxes in various kinds of plant canopies (e.g. Rosenberg, 1971; Aoki et al., 1975; Seo and Ohtaki, 1976). There are many variations in the formulation of Bowen ratio methods, some of which are described by Thom (1975).

2.3. Eddy correlation method

From the beginning of 1950, the eddy correlation method has been applied to the extensive study of the surface layer by Australian and American workers (e.g. Swinbank 1951, ; Taylor and Dyer, 1958; and others). In the turbulent flow, the vertical flux of carbon dioxide per unit mass of the fluid is given by

$$F_{\text{CO}_2} = \overline{w'c'} = \overline{w'c'}$$

where w is the vertical velocity and c the concentration of carbon dioxide. The overbar denotes the time average and prime the fluctuation. The sensible heat and water vapor flux induces the mean vertical velocity. The effects on CO_2 flux are estimated from the work of Webb et al. (1980). The eddy correlation method provides reasonably accurate estimates of fluxes more directly than the above-mentioned micrometeorological methods. However, instruments for measuring fluctuations must be so sensitive as to be able to respond to rapid changes in quantities such as velocity, temperature, humidity and carbon dioxide. Instruments, data acquisition and data processing systems have been developed to apply the eddy correlation method to estimating CO_2 flux in plant communities for many years. Next we will review fluctuation instruments and data acquisition systems.

2.3.1. Combination of turbulent correlation and gradient method

In order to apply the eddy correlation method to estimating CO_2 flux, it is necessary to develop CO_2 fluctuation sensor and a vertical velocity sensor. At

the end of the 1960's, sonic anemometer thermometers became practical for field use (Mitsuta, 1966), but CO₂ fluctuation sensors were not yet useful. Inoue et al. (1969) planned to develop the "Assimtron" for measuring CO₂ flux in the surface air layer. The design of the Assimtron is based on the turbulent correlation and gradient method. The instrument uses both the turbulent transfer coefficient for momentum and sensible heat, on the assumption that the turbulent transfer coefficient for CO₂ is also the same as that for momentum at nearly neutral stability and is also the same as that for sensible heat over a relatively wide range of stability. CO₂ flux was calculated by transmitting analog signals from CO₂ analyzer and fluctuation sensors such as vertical wind velocity, temperature to a specially designed analog computer. Uchijima (1970) reported that compared with the other two methods, the Assimtron considerably reduced the time consumed in processing primary measured data, and that it also improved the accuracy of the results. Seo et al. (1972) developed a similar though slightly different measuring system with an analog computer. After 1970, data acquisition systems changed rapidly from analog systems to digital systems, using mini-computers and personal computers with an AD converter.

2.3.2. Development of a CO₂ fluctuation sensor

For a long time researchers awaited the construction of an infrared gas analyzer to measure rapid fluctuations of CO₂ concentration. Holmes and Carson (1964) and Desjardins and Lemon (1974) tried to use a rapid-response infrared gas analyzer in an eddy correlation method. Ducting a parcel of air through the sample cell of a conventional infrared gas analyzer destroys the structure of the air parcel. Therefore, CO₂ fluxes were substantially underestimated due to the effects of slow response sensor time (see Garratt, 1975). Consequently, some allowance is necessary for the time delay and the loss of information at high frequencies.

Ohtaki and Seo (1976a, b) developed two models of a rapid open-path CO₂ device with a single beam and double beam system, which can measure fluctuations of CO₂ on site. The single beam device with a path length of 50 cm uses a 4.3 μm absorption band of CO₂. The device suffers from several limitations such as relatively high noise levels, inadequate stability and reproducibility. To overcome these difficulties, they developed an improved model based on a double beam system and equipped it with a detector of higher detectivity. The double beam device measures the CO₂ concentration by comparing the transmission in the 4.3 μm absorption band with that in the 3.9 μm reference band. A thermoelectrically cooled PbSe detector is kept at -20°C during operation. The IR device combined with a sonic anemometer makes it possible to determine the CO₂ flux by the eddy correlation method (Ohtaki, 1980). For field use, it still showed several problems, which were slow response and a rather bulky configuration, which disturbed the wind field. Ohtaki and Matsui (1982) improved the device by using a simple optomechanical system, with digital calculation on an arithmetic processor. The device was adequate in sensitivity and response time for simultaneous measurements of CO₂ and water vapor. At almost the same time, several such instruments have been constructed and used for measuring CO₂ flux over different kinds of vegetation (Brach et al., 1981, Desjardins et al., 1982) and over the ocean (Jones et al., 1978). The instrument developed by Bingham et al. (1978, 1983) was used over vegetation and on aircraft over sea and ice.

Jarvis and Sandford (1985) compared the properties of four open-path instruments for measuring CO₂ flux by eddy correlation. All four instruments use the 4.3 μm absorption band of CO₂. They also have solid state detectors and three of

them make use of a lead selenite device. The sample beam path length are very different among the four, depending on the relative positions of the source and detector. Elagina and Lazarev(1984) developed a CO₂ sensor with the 4.3 μ m absorption band, of which the design is quite similar to that of an infrared hygrometer reported by Elagina(1962).

2.3.3 International comparison of CO₂ fluctuation sensors

Experiments for intercomparison of fast response carbon dioxide sensors under field condition were made in Winnipeg, Canada in 1986 and in Zvenigorod, USSR in 1987(Volkov et al.,1989; Mitsuta et al.,1990). Agriculture Canada, University of Nebraska, Lincoln and Okayama University participated in the Winnipeg experiment and the Institute of Atmospheric Physics, USSR Academy of Sciences and Okayama University participated in the Zvenigorod experiment.

The carbon dioxide sensor of Agriculture Canada was the second revised version of the prototype model (Brach et al. 1981) with a path length of 20 cm. The CO₂ sensor of the University of Nebraska was a field model developed by Bingham et al. (1978), with a path length of 20 cm. The carbon dioxide-humidity sensor of Okayama University was that developed by Ohtaki and Matsui(1982). The other sensors were compared with the Okayama University sensor which was chosen as a reference.

A comparison of frequency response and the calibration of the CO₂ sensors were made by power spectral analysis. The normalized power spectra of Okayama University and the Institute of Atmospheric Physics showed the -2/3 slope in the high frequency range. This means that these two sensors are adequate for measuring the carbon dioxide flux in the atmospheric boundary layer. On the other hand, the power spectrum of Agriculture Canada fell off more rapidly than -2/3 due to the smoothing effect of the low-pass filter. Fluxes of carbon dioxide with the Agriculture Canada's sensor showed systematic underestimation of about 50 % compared with that of Okayama University. The improved Agriculture Canada sensor was fixed to the aircraft to measure the carbon dioxide flux in the upper layer during the experiment. After the Winnipeg experiment, the fourth version carbon dioxide sensor, which can simultaneously measure fluctuations in carbon dioxide and water vapor, was completed. The University of Nebraska's CO₂ sensor worked well, but a comparison with other sensors has not yet been presented. Innovations occur with each new fluctuation sensors.

2.4. CO₂ budget method

CO₂ exchange was estimated by measuring the rate at which air mass modification occurs while passing over a surface. The estimates require accurate measurements of CO₂ concentrations and velocities through the depth of the mixed layer. It also requires the assumption that the observed concentration modification is not a result of processes other than the surface flux. In practice, the budget method is not easy, because the average surface flux is small in comparison with other error terms of the mass budget equation which cannot be measured well.

The traverse method is often used to estimate the mass flux in some areas. (e.g. Yabuki and Aoki, 1973). Yamamoto et al. (1992) estimated intake rate of CO₂ due to the photosynthesis of vegetation under daytime conditions on Iriomote Island in March, by comparing the results of diffusion calculation with the differences between CO₂ concentrations observed on the down-wind side and up-wind side. They measured CO₂ concentrations of outside air introduced into the CO₂ fluctuation sensor set in the cabin of airplane.

3. Fluxes and fluctuation characteristics of CO₂ in plant communities

Volume II of 'Vegetation and The Atmosphere' (J.L. Monteith ed., 1976) describes many works on carbon dioxide exchange in several agricultural crops, different types of forests and ecosystems. Over the last ten years, measurements of fluxes and turbulent fluctuations of CO₂ have been made in various kinds of plant communities in many countries, using fast response sensors.

The similarities of the atmospheric fluctuations of carbon dioxide, water vapor and temperature over vegetated fields was studied (Ohtaki, 1985; Maitani and Ohtaki, 1989). The results showed a similarity in the fluctuation and transport processes of the scalar quantities under near neutral and unstable conditions. Ohtaki and Oikawa (1991) measured fluxes of carbon dioxide, water vapor and sensible heat by the eddy correlation method in a paddy field. They showed that the daytime totals of the downward flux of carbon dioxide depicted seasonal variation, reflecting photosynthetic activity or the leaf area index of the paddy crop. Maitani and Kashiwagi (1992) tried to measure diurnal variations of CO₂ fluxes at two heights above and within a rice field. They compared the turbulence statistics of humidity and carbon dioxide within and above plant canopies. The results showed that the magnitude or signs of turbulence statistics of each quantity were very different in daytime and nighttime and that they also depended on irrigation conditions.

Assembly of carbon dioxide-humidity sensor and three dimensional sonic anemometer thermometer with a path length of 10 cm above a rice field

Aircraft CO₂ flux measurements over a wheat crop were used to relate ground-based measurements on a regional scale (Desjardins and MacPherson, 1989). Recently, measurements of CO₂ flux by the eddy correlation method have been made in grass-lands (Verma et al., 1989) or in forests (Denmead et al., 1983; Verma et al., 1986) by the eddy correlation method.

4. CO₂ flux measurements in the future

(1) Future developments of CO₂ sensors with higher sensitivity will be required, using recent advances in electronics. These might enable us to estimate CO₂ fluxes in various kinds of surfaces, accurately and continuously.

(2) Further alternate comparison of different methods of CO₂ flux measurement are necessary to clarify the validity and the limits of each method.

(3) Cooperation between many scientists in various fields is needed to study CO₂ exchanges between plant communities and the atmosphere.

(4) As Desjardins and MacPherson (1989) noted, not only important ecosystems such as tropical forest, grass lands, tundra but also ecosystems such as boreal

forest, wet lands, oceans, savanna, peatlands and agricultural regions need to be studied. Their specific data will be useful for identifying the controlling factors of CO₂ budget on a global scale.

(5) International and multidisciplinary experiments are required to supply good information for the study of the CO₂ cycle between the biosphere and atmosphere. The eddy correlation method should provide standard data for tower-, shipboard- and aircraft-based CO₂ measurements.

Finally we expect the study of "CO₂ micrometeorology" to advance remarkably in the future.

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