A CO_2 Control System for a Greenhouse with a High Ventilation Rate

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Abstract

A simple CO_2 control system was developed for a greenhouse with a high natural or forced ventilation rate. This CO_2 control system maintains the difference in CO_2 concentration between inside and outside the greenhouse, ΔC, during daytime being small (ca. 5 μmol mol^{-1}), by supplying a variable amount of CO_2 gas with time. Results showed that this system worked satisfactorily, while the CO_2 concentration outside the greenhouse varied with time in a range between 350 and 450 μmol mol^{-1} with an average of 380 μmol mol^{-1}. In this system, the CO_2 supply rate was determined based on the time course of ΔC only, and does not consider any physical or physiological mechanisms of CO_2 balance in the greenhouse. Theoretically, the CO_2 supply rate is equal to the net photosynthetic rate of greenhouse crops (Pn), if both rates of CO_2 emitted from the substrate/floor and CO_2 exchange between inside and outside the greenhouse are negligibly small. Hence, this CO_2 control system will be useful not only for monitoring and increasing the Pn in a greenhouse with a high ventilation rate, but also as a diagnosis tool for monitoring the physiological status of greenhouse crops.

INTRODUCTION

A significant depression of CO_2 concentration (up to ca. 100 μmol mol^{-1}) often occurs on a fine day in a greenhouse with crops, even when its natural or forced ventilation rate is high (Yabuki and Imazu, 1965; Ito, 1970; Hanan, 1998). This depression of CO_2 concentration reduces the net photosynthetic rate of the greenhouse crops (Pn). This occurs because Pn decreases almost linearly with a decrease in the CO_2 concentration in a range roughly between 100 and 500 μmol mol^{-1} under wide ranges of photosynthetic photon flux and air temperature. To prevent a delay in crop growth due to the depression of CO_2 concentration inside the greenhouse, CO_2 control is necessary. A loss of CO_2 released to the outside, resulting in a decrease in the economic profit of the CO_2 control, is proportional to the difference in CO_2 concentration between inside (C_{in}) and outside (C_{out}), ΔC, and the greenhouse ventilation rate. The loss of CO_2 can be minimized by maintaining C_{in} at the same level as C_{out}, regardless of the greenhouse ventilation rate. The CO_2 control with $C_{in} \approx C_{out}$ for a greenhouse with open ventilators is widely used in European countries, such as UK and The Netherlands, during summer. Extension of this CO_2 control method is still limited in moderate and hot climate regions, especially in Asian countries such as Japan, Korea, and China, because of the high costs of investment in the CO_2 control system and liquid CO_2 gas (170 Japanese Yen/kg or 1.5 USD/kg). The objective of this study was to extend the CO_2 control method of $C_{in} \approx C_{out}$ for a greenhouse with a high ventilation rate in moderate and hot climate regions. To realize this CO_2 control method, a simple CO_2 control system was developed and tested in a small experimental greenhouse.

CONCEPT OF THE PROPOSED CO_2 CONTROL METHOD AND ITS BENEFIT

The goal of the abovementioned CO_2 control method is to increase Pn with minimal and efficient use of CO_2 in a greenhouse located in moderate and hot climate regions during daytime. During CO_2 control, the consumption rate of CO_2 can be given as the sum of Pn and the rate of CO_2 loss. The rate of CO_2 loss is given as the ventilation rate multiplied by

ΔC. Generally, in a greenhouse located in moderate and hot climate regions, the ventilation rate is high due to the necessity of lowering air temperature by ventilation. Hence, to decrease the consumption rate of CO_2 and simultaneous increase in Pn, C_{in} should be maintained at almost the same level as C_{out} (or $\Delta C \approx 0$). Although an increase in C_{in} by supplying CO_2 is relatively small (up to ca. 100 μmol mol^{-1}), Pn increases significantly. For example, when CO_2 gas was supplied to the greenhouse in order to increase C_{in} of 300 μmol mol^{-1} up to C_{out} of 380 μmol mol^{-1}, and the CO_2 compensation point of the crops is 100 μmol mol^{-1}, the expected increase in Pn is 40% (Fig. 1). In this case, the CO_2 gas supplied to the greenhouse never escapes from the inside, and all of the CO_2 gas supplied was fixed by the greenhouse crops through photosynthesis, regardless of the ventilation rate.

With this CO_2 control method, the CO_2 supply rate is equal to Pn, if both rates of CO_2 emitted from the substrate/floor and the CO_2 exchange between inside and outside the greenhouse are negligibly small compared with Pn. In other words, by using this CO_2 control system, Pn can be estimated simultaneously based on the CO_2 supply rate using no CO_2 balance model. By means of this estimation of Pn, the effect of environmental conditions (e.g., air temperature, shortwave radiation flux, etc.) on Pn can be evaluated readily (Matthews et al., 1987). Estimation of Pn can also be useful for monitoring or controlling crop growth. It should be noted that this CO_2 control system can be used not only for monitoring and increasing Pn, but also as a simultaneous diagnosis tool for the physiological status of greenhouse crops.

This CO_2 control system can be operated independent of other environmental control devices, such as heating, ventilation, shading, and watering devices, because only ΔC or C_{in} and C_{out} are measured and used for estimating the CO_2 supply rate. This operation method will contribute to simplifying the structure of the CO_2 control system, and thereby, to reducing the investment required for the CO_2 control system.

It is reported that the CO_2 enrichment at a high concentration (generally, more than 1000 μmol mol^{-1}) causes physiological disorders in several plant species. For example, the stomatal function of eggplants is remarkably sensitive to high CO_2 concentration, resulting in less translocation of calcium and boron (Hanan, 1998). However, this CO_2 control method will not be confronted by these problems, because C_{in} is equal to C_{out} or lower than the concentration reported to cause these physiological disorders.

A PROTOTYPE CO_2 CONTROL SYSTEM

The prototype CO_2 control system developed in this study consists of an infra-red type CO_2 analyzer, gas sampling lines made of Teflon, three solenoid valves, a liquid CO_2 gas container with a pressure regulator, and a float-type flow controller with a needle valve (Fig. 2). The CO_2 control system monitored C_{in} and C_{out} alternatively every 1 min, and determined the CO_2 supply rate. The CO_2 supply rate was regulated with the flow controller. Measurements and controls of C_{in} were made with a data controller. The CO_2 control system was tested in a naturally ventilated greenhouse with roof and side ventilators (4.8 m x 5.5 m x 3.4 m) at Chiba University, Japan (lat. 35º50', long. 139º50'). In the present experiment, only the roof ventilator was used to simulate a large-scale greenhouse, where the ventilation from the roof ventilator was dominant compared with that from the side ventilator. In the greenhouse, tomato (*Lycopersicon esculentum* Mill. "House Momotaro") plants, each with about 13 true leaves, were grown in pots at a planting density of 5.8 m^{-2}. Irrigation was made with a nutrient solution once or twice a day by using an automatic irrigation system.

In the first trial (May 11, 2004), liquid CO_2 was not supplied to the greenhouse to investigate how much C_{in} was decreased compared with C_{out}. Although the roof ventilator of the greenhouse was fully opened, C_{in} reached a concentration of 334 μmol mol^{-1} when C_{out} was 369 μmol mol^{-1}. In this condition, expected increase in Pn with the CO_2 control system was 13% (= ((369 - 5) - 100)/(334 - 100)). The value of ΔC decreased with time and became stable at ca. 13 μmol mol^{-1} between 11:30 and 14:30 (Fig. 3). This decrease in ΔC was because the air temperature inside the greenhouse was beyond an optimum range of Pn

(25-30°C, Khavari-Nejad, 1980) during the period (35.4 ± 0.5°C), suggesting that Pn would be increased further by the combined use of a cooling system and the CO_2 control system than by the single use of the CO_2 control system in a greenhouse located in moderate and hot climate regions. After 16:00, ΔC showed a negative value, indicating that the respiration rate of greenhouse crops became greater than Pn, despite the fact that the solar radiation inside the greenhouse was still 200 W m^{-2}. In the next morning, severe crop wilting was caused by a failure of the automatic irrigation system in the previous day. A decrease in soil moisture reflects a restriction of gas diffusion between a leaf and the surrounding air, such as Pn and transpiration, caused by stomatal closure (Kramer and Boyer, 1995). Generally, a decrease in Pn was observed prior to the observation of severe crop wilting. Hence, this accident caused by the failure of the irrigation system could be avoided if irrigation had been made based on the diagnosis using the CO_2 control system.

In the next trial (May 29, 2004), liquid CO_2 was supplied to the greenhouse during daytime whenever $(C_{in} + \Delta C) < C_{out}$, where ΔC is ca. 5 μmol mol^{-1}. Consequently, C_{in} could be maintained at a concentration of 5-10 μmol mol^{-1} below C_{out}, showing that the CO_2 control system worked satisfactorily (Fig. 4). In this condition, no supplied CO_2 escaped to the outside, regardless of its ventilation rate. Theoretically, Pn can be estimated based on the CO_2 supply rate, because CO_2 transferred by ventilation was small under the condition where C_{in} was nearly equal to C_{out} (Matthews et al., 1987). However, in the present experiment, the estimated Pn was smaller than the value of Pn of tomato plants reported by Zekki et al. (1999). This underestimation was partly because of the uneven distribution of C_{in} (data not shown). In a future study, an appropriate air sampling method and/or an air stirring method to obtain uniform distribution of C_{in} should be employed in the greenhouse.

CONCLUSION

In this paper, the concept and theoretical background of the CO_2 control method for a greenhouse in moderate and hot climate regions were described. Then, a simple CO_2 control system that was developed to realize the CO_2 control method was tested as a preliminarily study. Without CO_2 control, the CO_2 concentration inside the greenhouse (C_{in}) decreased by 35 μmol mol^{-1} during daytime, even when the roof ventilator was fully opened. On the other hand, by using the prototype CO_2 control system, C_{in} was successfully maintained at a level slightly lower (5-10 μmol mol^{-1}) than that outside (C_{out}). The expected increase in the net photosynthetic rate of greenhouse crops (Pn) was 13% if the CO_2 control system was employed. Although Pn was underestimated in this experiment, partly because of the uneven distribution of C_{in}, Pn could be estimated theoretically based on the CO_2 supply rate. Hence, this CO_2 control system can be considered as a potential tool for monitoring and increasing Pn and diagnosing the physiological status of greenhouse crops.

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Figures

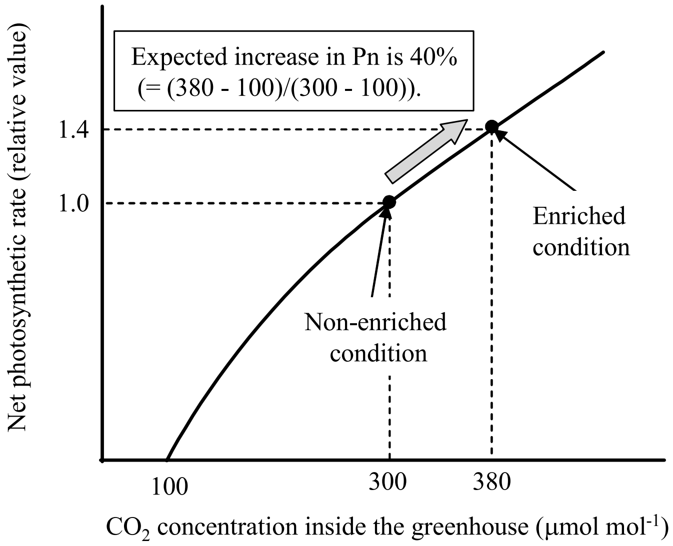

Fig. 1. Concept of the CO_2 control method for a greenhouse with crops in moderate and hot climate regions. In this method, depression of CO_2 concentration is avoided by supplying liquid CO_2 to the greenhouse. Suppose that CO_2 concentration inside the greenhouse was increased from 300 μmol mol^{-1} to 380 μmol mol^{-1} (or CO_2 concentration outside the greenhouse) by CO_2 control and a CO_2 compensation point of the greenhouse crops is 100 μmol mol^{-1}; the expected increase in the net photosynthetic rate of greenhouse crops (Pn) is 40%.

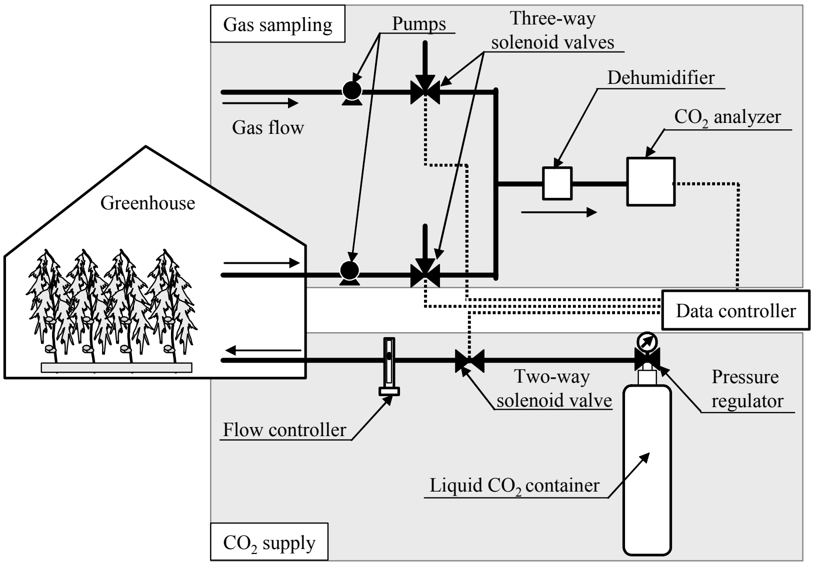

Fig. 2. Schematic diagram of the prototype CO_2 control system. Solid and dotted lines indicate the gas and signal flows, respectively.

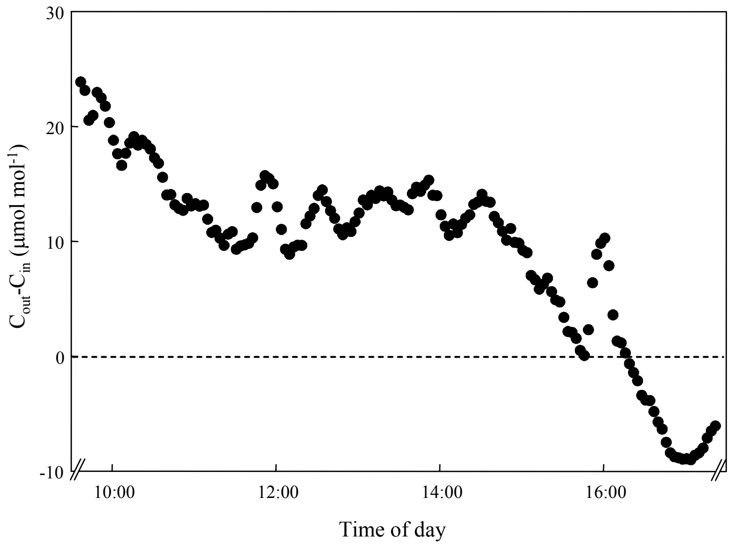

Fig. 3. Time course of the difference of CO_2 concentration between inside (C_{in}) and outside (C_{out}) the greenhouse without CO_2 control on May 11, 2004. Running averages for 12 min were plotted. Dotted line indicates $C_{in} = C_{out}$.

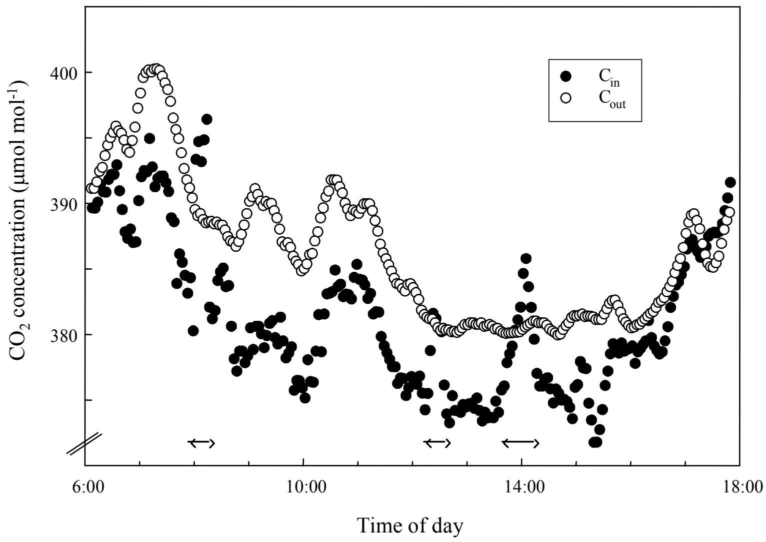

Fig. 4. Time courses of CO_2 concentrations inside (C_{in}) and outside (C_{out}) the greenhouse with CO_2 control on May 29, 2004. Running averages for 12 min were plotted. Closed and open circles indicate C_{in} and C_{out}, respectively. Horizontal arrows indicate the durations of presence of person(s) inside the greenhouse.