An Idea of Concentration Gradient FACE (Free Air CO₂ Enrichment) and a Preliminary Experiment of Its Control Using a Neural Network

Kenji KURATA,¹ Kazuyuki SEYAMA,¹ Hirofumi NAKAMURA,² Masumi OKADA²
and Kazuhiko KOBAYASHI¹

¹ Graduate School of Agricultural and Life Sciences, University of Tokyo,
Bunkyo-ku, Tokyo 113–8657, Japan

² National Agricultural Research Center for Tohoku Region, Morioka, Iwate 020–0198, Japan

(Received June 1, 2004)

In existing FACE (Free Air CO₂ Enrichment) systems, efforts have been made to maintain the CO₂ concentration within a FACE ring at the setpoint value. Therefore, effects of only one elevated CO₂ concentration on plants and/or ecosystems can be examined with one ring. The basic idea of the present study was, instead of controlling the CO₂ concentrations within a ring at a constant value, to create and maintain a constant CO₂ concentration gradient within a ring. In this way, examinations of the effects of different CO₂ concentrations on plants and/or ecosystems would be realized using one ring. An artificial neural network was applied to control the CO₂ gradient within a ring of a stretched hexagon with ten CO₂ emitting tubes. The results of the experiments showed that when the wind speed was more than the detectable range by the anemometer (about 30 cm s^{−1}), a concentration gradient was in most cases observed, though not completely the same as the target gradient. When the wind speed was less than the detectable value, the CO₂ concentrations within a ring rose far above the target values and the gradient was not created.

Keywords: climate change, concentration gradient FACE, Free Air CO₂ Enrichment (FACE), Kalman filter, neural network

INTRODUCTION

Predicting effects of increasing atmospheric CO₂ concentration on plants and/or ecosystems has been one of the major research topics in global change studies, and many studies have been conducted on this point using controlled environment cabinets, greenhouses and/or open top chambers. However, more than a decade ago it was pointed out that all types of enclosures, such as greenhouses, open top chambers, produce changes in plant growth conditions including light intensity, light quality, temperature, humidity, wind speed, compared to open field conditions (e.g., Hendry et al., 1993), and another experimental method named Free Air CO₂ Enrichment (FACE) was proposed, which was thought to be free from artifacts due to enclosing plants with films or glasses. In FACE, CO₂ gas is released in an open field and effects of elevated CO₂ concentration on plants and/or ecosystems are studied.

Corresponding author: Kenji Kurata, fax: +81-3-5841-8172,
e-mail: akurata@mail.ecc.u-tokyo.ac.jp

In the existing FACE experiment systems, the experimental plots are enclosed with either an array of vent pipes (e.g., Lewin et al., 1994) or tubes (e.g., Okada et al., 2001) from which CO₂ gas is released. The CO₂ concentration of the released air or the pure CO₂ gas release rate is controlled so that the CO₂ concentration within the enclosure (hereafter, ring) is maintained at a constant level (setpoint). The spatial as well as temporal variations of the CO₂ concentration within the ring are to be minimized.

In the FACE experiments hitherto, only one elevated CO₂ level has been used, because examinations of the effects of several elevated CO₂ concentrations on plants and/or ecosystems were not practical due to the funding and/or spatial constraints. In this report we propose a concentration gradient FACE, in which, instead of a constant CO₂ concentration within a ring, a constant spatial CO₂ concentration gradient is maintained by controlling the CO₂ gas release rate. In other words, in one ring a range of CO₂ concentrations from elevated to nearly ambient level would be realized, so that effects of various CO₂ concentrations might be tested efficiently.

One of the major difficulties in realizing a gradient FACE system is the control of CO₂ release. In existing FACE systems, the control variable is the CO₂ concentration at a fixed point (mostly at the center of the ring). By contrast, in a gradient FACE system, the control variables are those at multiple points. Changing the CO₂ release rate for one point simultaneously alters the CO₂ concentrations at other points, and the relationship among CO₂ release and the CO₂ concentrations at the multiple points are aerodynamically complicated. It is hardly possible to theoretically deduce a control algorithm in a gradient FACE under ever-changing micrometeorological conditions (wind speed, wind direction, and turbulence). To avoid this difficulty, we applied an artificial neural network (hereafter, NN) to control CO₂ release in the gradient FACE. The NN learns the relationships among the operations and control variables' reactions from the past experiences and applies the learned relationships to the control. Additionally, following advantages are expected in applying NN to this problem: 1. Unlike the fixed control algorithm, the more it experiences (as the experiment goes on), the better it could control. 2. It can adjust the control method to the changing environment. For example, as the plants in a ring grow, the air flow pattern may be changed from that at the beginning of the experiment. Dominant wind direction may also change as the season progresses. The NN can adapt its control methods to these changes. 3. The same method can be used in different locations. Because there are no parameters which need location-specific tuning before the experiment, the software in one place can be used in another place without any adjustments. Also, if the ring layout remains the same, the developed program can be applied even if the control hardware (e.g., mass flow controller) is different from the original one, because the program does not contain any hardware-specific parameters.

The objectives of the present study were to develop a gradient FACE system, to test its feasibility, and to locate problems in the field.

MATERIALS AND METHODS

In the existing FACE systems, the CO₂ emitters are arranged in a circle or a circle-like configuration (e.g., an octagon in Rice FACE, Okada et al., 2001). However, adopting these shapes to the gradient FACE was thought to be difficult for the concentration control. It was, instead, supposed that a shape of stretched ring, or a very long oval, has advantages as follows. Let us assume that the setpoint at Point A in Fig. 1 is higher compared to that at Point B. If the wind direction is α , CO₂ would be released at the rate from Point D and near around to maintain the concentration at Point A at the setpoint, which would inevitably make the concentration at Point C nearly the same value at Point A. However, if the wind direction

Fig. 1 Illustration of the disadvantage of a circular ring for a gradient FACE experiment (see text for details).

Fig. 2 Experimental setup.

is β , the same argument holds for the concentrations of Point B and C, and the concentration at Point C would be nearly equal to that at Point B. Thus, the concentration at Point C would vary according to the wind direction, if a constant concentration gradient on the line through Points A and B should be maintained. A narrow ring shape can be regarded to the area sandwiched by two thin broken lines in Fig. 1, which excludes the area where the concentrations vary much due to the changing wind direction.

For this reason, a shape of a stretched ring was adopted for the configuration of CO₂ emitters. The experimental setup is schematically illustrated in Fig. 2. The shape of the ring was a stretched hexagon, composed of ten 5 m long plastic tubes. These tubes were the same as those in Okada et al. (2001). The tubes are commercially available irrigation ones (Kiriko type-R, Mitsui Kagaku Iattech), with a diameter of 4 cm and have numerous tiny holes (0.5–0.9 mm in diameter) on one side. Pure CO₂ gas was released through these holes. Along the major axis of the hexagon, five CO₂ measuring points were located at 50 cm height with 3 m intervals. There was no vegetation on the ground during the experiments. CO₂ analyzers (ZFP9, Fuji Denki) were put in boxes and buried just below each measuring point to minimize the time lag in the measurements. Another same type CO₂ analyzer was used apart from the ring to measure the background CO₂ concentration. An aerovane (GRS203, Makino) was placed beside the ring at 1 m height. The minimum detectable wind velocity was about 30 cm s⁻¹.

The experiments were conducted at the Rice FACE site in Shizukuishi, Japan (e.g., Okada et al., 2001) in the fall of 1999 after the harvest. The CO₂ gas supply facilities in the Rice FACE experiment were used in this experiment. Pure CO₂ gas was transferred from the tank to the experiment site and its pressure was reduced by a pressure regulator to 0.3 MPa.

Because the experiment was conducted in an open field without any remarkable obstacles against the airflow, the experiment site was regarded to be symmetric with respect to the main axis of the hexagon ring. Five solenoid valves (FAG51-8/10-4-12C, CKD) were used to control the CO₂ gas paths, so that CO₂ gas was released from the five tubes located windward with respect to the ring axis. Flow rates of pure CO₂ gas from the five windward tubes were regulated by mass flow controllers (3655-1/4SW-CO₂-50SLM, Koflock). Two controllers were used in parallel for each tube to obtain the maximum flow rate of 72 L min⁻¹.

All the measurements, controls, monitoring, and recording were conducted using a personal computer, attached with an AD board (AZI-3133, Interface), a DA board (AZI-3329, Interface), and a relay board (AZI-2503, Interface). The control and learning software was written in Visual C++ language.

The NN applied composed of three layers: input layer (23 nodes), middle layer (23 nodes), and output layer (five nodes). Input data were: wind direction, wind speed, background CO₂ concentration, CO₂ concentration setpoints at the five locations along the CO₂ gradient, five CO₂ concentrations (present values), five CO₂ concentrations (5 s before present), and five CO₂ concentrations (10 s before present). Thus, not only the present values of the CO₂ concentrations but also the past values were included, hoping an effect similar to the D component of the PID control logic. The CO₂ concentrations setpoints at the five measuring points were 300, 250, 200, 150, and 100 $\mu\text{mol mol}^{-1}$ above the ambient concentration. Output data from the NN were CO₂ gas release rates from the windward five tubes. Note that the causal relationships were partly reversed in the input-output relationships in the NN: CO₂ gas release rates effects the CO₂ concentrations at the measuring points, while in the NN, the former are the outputs and the latter are the inputs. In this way, the outputs of the NN could be directly applied to the control. Measurements and control were conducted every 5 s.

The NN simultaneously learned from the past 100 examples as a background program. It stopped learning from the retaining examples either when it converged or when it repeated learning 100 times. The convergence criterion was:

$$\log_{10} (\text{average of absolute values of the errors}) < -1.6,$$

where 'average' means the average of the five absolute errors (normalized to take values between 0 and 1), further averaged over the 100 examples. The learning algorithm was the Kalman filter method (Murase et al., 1994). It took more than 4 or 5 min before it converged or learning was repeated 100 times. Then, the NN abandoned the oldest 30 examples and, instead, introduced new 30 examples which were selected from those acquired after the last renewal of the examples. After replacement of the examples, NN resumed learning. The newly introduced examples were the latest 10 successive examples (5 s intervals), 10 every other examples (10 s intervals) gathered before the above-mentioned 10 successive examples, and 10 examples at the interval of 15 s gathered before the above-mentioned 10 every other examples.

Before the start of the NN control, 100 examples were created by the following control algorithm and these data were fed to the NN to initiate learning. In this beginning phase, CO₂ release from a tube was regarded to affect only one CO₂ measuring point which was the nearest one from the line drawn from the center of the tube to the wind direction. Release rate was controlled based on the PD algorithm.

RESULTS AND DISCUSSION

Many trials were conducted. Here, the results of the about 900 min long experiment are presented. Figure 3 shows the temporal variations of the wind speed and the average error (absolute values of the differences between the setpoint CO₂ concentrations and the measured

ones, averaged over the five measuring points). The test began at 18 : 30. It can be seen that during the night, the wind speed was very low and sometimes (about 300–800 min in Fig. 3) below the detectable limit by the anemometer. In these cases, the error became remarkable. Figures 4–9 show some examples, together with the wind speed and wind direction data. One minute after the beginning of the experiment (Fig. 4), the wind blew at more than 1 m s^{-1} and clear concentration gradient was observed, although slightly higher than the setpoints values. However, as the experiment went on, this gradient became partly corrupted (Fig. 5 : both ends) or the gradient became smaller (Fig. 6). Though somewhat degraded, we could observe

Fig. 3 Temporal variations of the wind speed and the average error (absolute values of the differences between the setpoint CO_2 concentrations and the measured ones, averaged over the five measuring points).

Fig. 4 (a) Wind speed and wind direction between 1 and 2 min after the start of the experiment. Wind direction is defined to be 0 when it blows parallel from the measuring point 5 to 1. (b) CO_2 concentration profiles during the same period. The thick line indicates the setpoint values. Other lines indicate measured values taken at 10 s intervals.

Fig. 5 Same as Fig. 4 except for the period (from 8 to 9 min).

Fig. 6 Same as Fig. 4 except for the period (from 12 to 13 min).

concentration gradient in most cases when the wind was detectable. However, when the wind was less than the detectable range (Figs. 7 and 8), the measured concentrations were much higher than the setpoints. Difficulties of controlling the CO₂ level at the time of low wind speed have been reported also in the existing FACE systems (e.g., Okada et al., 2001). The same arguments also hold for the gradient FACE. But, when the wind blew again in the morning, the gradient was recovered, though not completely (Fig. 9). Table 1 shows the average CO₂ concentrations at each point. As a whole, the realized concentrations were

Fig. 7 Same as Fig. 4 except for the period (from 60 to 61 min).

Fig. 8 Same as Fig. 4 except for the period (from 480 to 481 min).

somewhat higher than the setpoint values, even when the wind blew, and reversed gradients were partly observed (points 2 and 3: points 4 and 5). However, when the wind was not detectable, the realized concentrations were remarkably higher than the setpoints values, and the gradient was not constructed.

Thus, we can conclude that, as long as the wind speed is higher than the detection limit (about 30 cm s⁻¹), NN control of the gradient FACE has a very high potential, though at the present state of the installation, its behavior is not yet satisfactory. The problem is, however,

Fig. 9 Same as Fig. 4 except for the period (from 900 to 901 min).

Table 1 Average CO₂ concentrations at each point (μmol mol⁻¹).

	Point 1	Point 2	Point 3	Point 4	Point 5
Average of the setpoint	719	669	619	569	519
Average across the period of detectable wind speed	964	858	879	788	831
Average across the period of undetectable wind speed	1,453	1,321	1,433	1,174	1,288

the method of control at the time of undetectable wind. We speculate that NN control under the undetectable wind conditions might not be promising and other methods would be required. For example, a simple method such as releasing CO₂ at higher rates from the tubes near the measuring points with the higher setpoint values is expected to work better than NN. Such combinations of NN with other methods is one of the way to follow in the future.

As to NN, decreasing the number of inputs is expected to improve its behavior (faster convergence). For example, in this experiment, input variables included five setpoint values, a background value, and five measured values. These 11 values could be integrated into five errors (differences between the setpoint and measured values). Thus, the number of inputs can be reduced by six. The shape of the ring is another issue. The present shape was determined mostly by intuition. We conceived, as mentioned above, that a narrow shape would be easier to create a concentration gradient than the circle or circle-like shapes. Admittedly, the shape has not been optimized. The optimal ratio of the length to the width should be determined not only from the control viewpoint but also from the viewpoint of the requirements for physiological research in the future. Last but not least, choice of the experiment site is one of the key points for the success of the gradient FACE. Stable wind would remarkably reduce the difficulties in controlling the gradient FACE. Our results showed that when the wind was undetectable, control became extremely difficult. Therefore, constantly blowing wind would facilitate the control. It is also expected that if the wind direction is stable, the control would

become much easier. In this experiment, we tried to set the ring with the main axis perpendicular to the most frequent wind direction at the experiment site. Unfortunately, because of the lack of the reliable wind direction data, this could not be realized. However, if the ring could be set in this way, and if the wind direction would be stable, much higher performance of the NN-controlled gradient FACE, compared with the present one, would be expected.

This study was partly supported by Grant-in-Aid for Scientific Research (A)(2), No. 07556108, the Ministry of Education, Culture, Sports, Science and Technology, Japan.

REFERENCES

- Hendry, G., Lewin, K., Nagy, J. 1993. Control of carbon dioxide in unconfined field plots. In "Design and Execution of Experiments on CO₂ Enrichment" (ed. by Schulze, E. D., Mooney, H. A.). Commission of the European Communities, Luxemburg, p 309-327.
- Lewin, K. F., Hendrey, G. R., Nagy, J., LaMorte, R. L. 1994. Design and application of a free-air carbon dioxide enrichment facility. *Agric. For. Meteorol.* **70**: 15-29.
- Murase, H., Koyama, S., Ishida, R. 1994. *Kalman Neuro Computing by Personal Computers*. Morikita Shuppan, Tokyo, Japan (Japanese text).
- Okada, M., Lieffering, M., Nakamura, H., Yoshimoto, M., Kim, H. Y., Kobayashi, K. 2001. Free-air CO₂ enrichment (FACE) with pure CO₂ injection: Rice FACE system design and performance. *New Phytologist* **150**: 251-260.
-

〈和文抄録〉

濃度勾配型 FACE（開放型高 CO₂ ガス濃度）のアイデアとニューラルネットワークを用いたその制御の予備的な実験

蔵田 憲次¹・瀬山 和幸¹・中村 浩史²・岡田 益己²・小林 和彦¹

¹ 東京大学大学院・² 東北農業研究センター

耕地あるいは自然生態系に直接 CO₂ ガスを放出して、一定区画内の CO₂ ガス濃度を高く維持し、作物あるいは自然生態系の反応を調べる FACE 実験は、世界的に広く行われている。しかし、今までの FACE システムでは、CO₂ ガスの設定値は 1 つだけで、異なる複数の CO₂ ガスの影響は調べられなかった。そこで、区画内に CO₂ ガス濃度の勾配を作り出すシステムを考え、その一定の濃度勾配を作出・維持するためにニューラルネットワークにより制御を行った。実験の結果、風速計が感知できないほどの微風時には、濃度勾配を維持できなかったが、ある程度の風速があるときは、設定値からずれはしたものの、濃度勾配を作出することができた。