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Research Paper

Efficiency of carbon dioxide enrichment in an unventilated greenhouse

Takeshi Kuroyanagi [a,*], *Ken-ichiro Yasuba* [b], *Tadahisa Higashide* [c], *Yasunaga Iwasaki* [c], *Masuyuki Takaichi* [c]

[a] *Western Region Agricultural Research Center, National Agriculture and Food Research Organization (NARO), Ikano 2575, Zentsuji, Kagawa 765-0053, Japan*

[b] *Okayama University, Tsushima-naka 1-1-1, Kita, Okayama 700-8530, Japan*

[c] *Institute of Vegetable and Tea Science, National Agriculture and Food Research Organization, Kannondai 3-1-1, Tsukuba, Ibaraki 305-8666, Japan*

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In recent years, efforts have been made to utilise carbon dioxide (CO_2) enrichment and reduce the emissions of CO_2 from greenhouses. In this study, efficiency of CO_2 enrichment in an unventilated greenhouse was investigated based on balance measurements of CO_2 in the short-term and an estimate of CO_2 leakage in the medium-term. A greenhouse covered with plastic film (floor area 178 m^2) was used. Pure CO_2 was supplied to a tomato crop trained to a high-wire system, maintaining a CO_2 concentration nearly 1000 μmol [CO_2] mol^{-1} [air] during daylight. For CO_2 balance measurements, the leakage rates, the amount of CO_2 leakage and crop uptake were derived hourly from a CO_2 balance equation of greenhouse air and leakage measurements using a tracer gas technique. The leakage rate of the unventilated greenhouse was within similar ranges found in literatures investigating other types of greenhouses. The amount of CO_2 leakage was comparable to crop uptake in windy or overcast conditions. The efficiency of CO_2 enrichment in the medium-term was estimated using the regression equation of the leakage rate, measurements of outside wind velocity, amount of CO_2 supply, and CO_2 concentrations inside and outside. The estimated results in the medium-term showed an average efficiency of 45.5%; the highest efficiency was around 50%. Higher efficiencies were achieved when it was less windy and there was higher solar radiation.

1. Introduction

Since the beginning of the 19th century, the effects of carbon dioxide (CO_2) enrichment on plant growth have been extensively investigated. As a result, CO_2 enrichment recognised as one of the most important measures for increasing greenhouse productivity (Wittwer & Robb, 1964). So far, most studies have focused on the positive and negative effects of CO_2 enrichment on plant growth, such as increased yields, damage due to by-product air pollutants, or damagingly high concentrations of CO_2. Suitable CO_2 concentration ranges for vegetables and flowers have been proposed based on the numerous literature data (Mortensen, 1987).

* *Corresponding author*. Tel.: +81 877 63 8116; fax: +81 877 62 1130.
E-mail address: tkuro@affrc.go.jp (T. Kuroyanagi).

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Nomenclature

A	the greenhouse floor area, m^2
C	CO_2 concentration, g [CO_2] m^{-3} [air]
C'	tracer gas concentration, μmol [tracer] mol^{-1} [air]
dq_C	relative error of a CO_2 densitometer, %
$dq_{C'}$	relative error of a tracer gas densitometer, %
dq_{dC}	relative error of temporal variation of CO_2 concentration, %
dq_{φ_l}	relative error of CO_2 leakage rate, %
dq_{φ_p}	relative error of net CO_2 uptake rate of crop, %
dq_{φ_s}	relative error of CO_2 supply rate, %
n	the leakage rate, h^{-1}
t	time, min
U	outside windspeed, m s^{-1}
V	the greenhouse volume, m^3
ε_a	the amount of residual CO_2 after daylight, g [CO_2] m^{-2}
ε_b	the amount of residual CO_2 before daylight, g [CO_2] m^{-2}
η	the efficiency of CO_2 enrichment, %
φ_l	the CO_2 leakage rate, g [CO_2] m^{-2} min^{-1}
φ_p	the net CO_2 uptake rate of a crop, g [CO_2] m^{-2} min^{-1}
φ_s	the CO_2 supply rate, g [CO_2] m^{-2} min^{-1}

Subscripts

in	inside the greenhouse
out	outside the greenhouse
1, 2	time

Optimal control strategies for CO_2 enrichment have been investigated based on models. The principle underlying these strategies is a maximisation of the financial margin between crop value and the costs of CO_2 used for enrichment (Nederhoff, 1988). This concept has been applied to investigate the critical point of CO_2 enrichment using liquid CO_2, a waste CO_2 from other industries, or CO_2 produced by burning natural gas (Chalabi, Biro, Bailey, Aikman, & Cockshull, 2002a, 2002b). Kläring, Hauschild, Heißner, and Bar-Yosef (2007) experimentally tested a derivative strategy in which CO_2 concentration inside the greenhouse was maintained by adding pure CO_2 at a level similar to that found outside when a CO_2 depletion inside occurred.

Model-orientated investigations are effective in identifying optimal strategies for increasing yields whilst decreasing CO_2 consumption. For example, the photosynthetic rates of tomato, cucumber, sweet pepper, and chrysanthemum have been investigated using a CO_2 balance model in greenhouse compartments enriched with CO_2 (Körner, Van't Ooster, & Hulsbos, 2007; Nederhoff, Gijzen, & Vegter, 1988; Nederhoff & Vegter, 1994a). However, the objective of these studies was to parameterise, or validate, a model for plant photosynthesis. Chalabi and Fernandez (1994) estimated not only the net photosynthesis of plants, and CO_2 leakage from a greenhouse using a CO_2 balance equation, and suggested that underestimation of the real ventilation rate might result in unreliability of the estimated CO_2 fluxes. The aforementioned previous studies focused primarily on estimating net photosynthesis and the resultant marginal costs and yield, and have paid little attention to accurate estimates of efficiency of CO_2 enrichment.

Winter is the most suitable season for CO_2 enrichment because the greenhouse ventilators are usually kept closed. The concept of a closed greenhouse (Opdam, Schoonderbeek, Heller, & de Gelder, 2005) realises both a favourable environment for crop growth and a minimisation of CO_2 emissions. However, it might be intuitively assumed that the total amount of CO_2 supplied to greenhouses is not used for crop photosynthesis, and that a percentage of the supply leaks out, even under unventilated conditions.

All amounts of CO_2 emissions are regarded as environmental burdens when the CO_2 is produced especially for enrichment purposes. In cases where the CO_2 originates from heaters and combined heat and power (CHP) in greenhouses, or as a waste from other industries, the emissions from enriched greenhouses should be excluded from estimations of carbon offsets. Even though CO_2 enrichment using CHP generators is regarded as helping reduce CO_2 emissions in the Netherlands (Nederhoff, 2006), this framework acts as a substitute for electricity supply from power plants at the level of a country or an economic community. However, in both cases, the amount of CO_2 that leaks from greenhouses enriched with CO_2 remains extremely limited. Research into the efficiency of CO_2 enrichment in unventilated greenhouses remains to be elucidated.

This present study was performed to evaluate the CO_2 leakage and the efficiency of CO_2 enrichment in an unventilated greenhouse in Japan. The balance measurements of CO_2 in an unventilated greenhouse were conducted to estimate the hourly CO_2 leakage and the crop uptake over four days in winter. The efficiency of CO_2 enrichment in the medium term was then presented through an estimation of the leakage rate in relation to the weather conditions.

2. Material and methods

2.1. Model description

The balance equation of CO_2 in a greenhouse is described as a function of the air exchange, crop net uptake, inside and outside concentrations and supply (Gijzen et al., 1998). Under the assumption that greenhouse air is perfectly stirred, and the floor is not a sink or source of CO_2, the balance equation in an unventilated greenhouse is:

$$\frac{V}{A}\frac{dC_{in}}{dt} = \varphi_s - \varphi_p - \varphi_l \quad (1)$$

where A is the greenhouse floor area (m^2), C is CO_2 concentration (g [CO_2] m^{-3} [air]), t is time (min), V is the greenhouse