Note

# Elevating Carbon Dioxide in a Commercial Greenhouse Reduced Overall Fuel Carbon Consumption and Production Cost When Used in Combination with Cool Temperatures for Lettuce Production

Jonathan M. Frantz[1]

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Summary. **Greenhouses that are well sealed can result in carbon dioxide ($CO_2$) drawdown and suppressed plant growth. While growers can add supplemental $CO_2$, it is unknown how supplemental $CO_2$ fits within the framework of sustainable crop production in greenhouses. In this study, supplemental $CO_2$ was used in combination with reduced temperatures to evaluate the productivity of 'Grand Rapids' lettuce (*Latuca sativa*) compared with a traditionally maintained, warmer, and well-insulated greenhouse without supplemental $CO_2$ at a commercial facility. Simulations using Virtual Grower software based on identical greenhouses compared fuel use and carbon (C) consumed because of heating and $CO_2$ supplementation. Models were verified with measurements in a well-sealed commercial greenhouse; $CO_2$ quickly decreased to below 300 ppm in a nonsupplemented greenhouse containing plants. Supplemental $CO_2$ boosted total leaf number and mass of lettuce even though temperatures were maintained 3 °F lower in elevated $CO_2$ than in the traditional management scenario. Maintaining a cooler greenhouse but adding $CO_2$ decreased total carbon (C) consumed (by combined fuel use and $CO_2$ supplementation) by 7% during the 3-month season that required a well-sealed greenhouse. Additionally, fuel savings because of lower temperature set points paid for the cost of adding $CO_2$. The use of $CO_2$ enrichment should be considered as a tool in sustainable systems when its use can counteract the plant growth and development reductions brought on by lowered temperatures.**

Greenhouses are typically heated during the winter to maintain markets or to start plants early enough to meet spring consumer demand. Growers must decide which greenhouses to minimally heat and which to maintain at higher temperatures to meet market demands. Coupled with this decision is choosing the extent of insulation to install and gaps to seal, which will reduce air infiltration. Air infiltration can lead to a great deal of heat loss, but greenhouses that are sealed too tightly could have high humidity, inadequate air supply for heater intake or exhaust (Giacomelli and Roberts, 1993), and reductions in the atmospheric $CO_2$ concentrations.

The drawdown of $CO_2$ in a closed system is an often ignored issue and in some instances, can lead to plant growth problems. Measurements as low as 175 ppm $CO_2$ inside greenhouses have been recorded (Frantz and Schmidlin, 2009), and $CO_2$ concentrations are commonly 300 to 330 ppm (390 ppm atmospheric or outside), even in well-ventilated greenhouses. This drawdown in $CO_2$ has been used in laboratory settings to document photosynthesis in the day time (Wheeler, 1992). It is not widely appreciated how quickly this drawdown can occur since many assume that greenhouses, even those that are well sealed and insulated, leak enough to maintain adequate $CO_2$ for plant growth.

An option in counteracting potential $CO_2$ drawdown in greenhouses is to supply supplemental $CO_2$. A recent review describes many of the options and costs associated with different $CO_2$ supplementation systems (Blom et al., 2009). Sustainable production practices have increased in recent years in greenhouse systems (Dennis et al., 2010), but it is unknown how the use of supplemental $CO_2$ fits within the framework of sustainable controlled agriculture. In this study, the use of supplemental $CO_2$ was explored in combination with reduced temperatures. The objective was to compare lettuce growth within a low-temperature greenhouse supplemented with $CO_2$ against lettuce growth within a more traditional warm, well-insulated greenhouse, without $CO_2$ injection. This experiment was combined with simulations using Virtual Grower software (Frantz et al., 2010) that compared cost, fuel use, and C consumed because of heating and $CO_2$ supplementation between the two greenhouses.

## Materials and methods

Two identical commercial greenhouses were used as the experimental test sites. Greenhouses were located in Delta, OH (lat. 41°34′N, long. 84°0′W, elevation 722 ft), and consisted of single-span, double polyethylene-glazed greenhouse (29 × 184 ft). Side walls were 5 ft tall, the height at the middle of the greenhouse was 14 ft, and the greenhouses were single peak design. In one greenhouse, a $CO_2$ controller was installed (model iGS-061; SpecialtyLights.com, Boca Raton, FL) along with a two-way solenoid (model SV122; Omega Engineering,

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USDA-ARS, Greenhouse Production Research Group, 2801 W. Bancroft, MS 604, Toledo, OH 43606

[1] Corresponding author. E-mail: jonathan.frantz@ars.usda.gov.

Stamford, CT) to allow $CO_2$ to be injected into the greenhouse air ducts along each side of the greenhouse from a liquid $CO_2$ source. This also ensured that all injected $CO_2$ would be immediately mixed throughout the greenhouse. The day-time $CO_2$ set point was 500 ppm, while night-time $CO_2$ was not controlled. The second greenhouse (control house) did not have $CO_2$ control. Atmospheric $CO_2$ measurements made at a variety of places around the northern hemisphere indicate that outside $CO_2$ concentration was between 392 and 395 ppm during that winter (U.S. Dept. Commerce, 2011). Basic $CO_2$ response curves for C3 plants predict that the 0 to 500 ppm $CO_2$ range is within the linear response for photosynthesis, so a difference of even a few parts per million would directly influence the photosynthetic rate for lettuce (Taiz and Zeiger, 2002).

In addition to the $CO_2$ controller, which constantly measured ambient $CO_2$ concentrations to add additional $CO_2$, independent measurements were made. About three to four times per week, $CO_2$ concentrations were measured during the day with a hand-held $CO_2$ and temperature meter (Telaire 7001; GE Sensing, Billerica, MA) to verify the set point, monitor the control house $CO_2$ environment, and monitor air temperature in both greenhouses. Humidity was not monitored. The temperature set point in the $CO_2$-controlled greenhouse was 62 °F constant and that in the control house was 65 °F constant. In the Ohio area, calculations have indicated that for every 1 °F decrease in set point, a 3% savings in energy cost can be realized (P. Ling and C. Pasian, personal communication). A 3 °F would therefore result in nearly 10% fuel savings.

Lettuce seeds were sown in soilless rooting cubes (Oasis, Cleveland, OH) on 22 Nov. 2008. After 10 d (1 Dec.), 10 seedlings were transplanted individually into 6-inch pots (1.3 L) filled with sphagnum peat-based substrate (Sunshine Mix 1; Sun Gro Horticulture, Bellevue, WA). Five plants were grown in each greenhouse for 45 d. At the end of the growth period, leaves were removed, counted, and dried in a forced air oven (55 °C for 3 d) for dry weight measurement. The remaining area in the greenhouses was filled with stock geranium (*Pelargonium ×hortorum*) for cutting propagation. The large amount of actively growing plants in both greenhouses contributed to the $CO_2$ drawdown during the day and allowed the $CO_2$ differences to occur in the uncontrolled $CO_2$ greenhouse compared with the greenhouse that was actively maintained at a set point of 500 ppm $CO_2$.

Fuel use simulations were performed using Virtual Grower software (Frantz et al., 2010). A previous study (Frantz et al., 2010) evaluated this greenhouse as part of the verification of Virtual Grower's accuracy. Predicted fuel use and cost was found to be within 5.1% to 5.6% of actual costs based on the grower's heating bills. While it would have been more accurate to measure the actual fuel consumed by installing fuel meters on each greenhouse bay, the model's previous accuracy indicated that C, fuel, and cost predicted from Virtual Grower would fairly represent this commercial facility.

A single-bay greenhouse with double polyethylene covering with sizes matching the experimental greenhouses was used as the structure within the Virtual Grower software (Frantz et al., 2010), with Toledo, OH, weather as the weather database. A temperature set point of either constant 62 or 65 °F was simulated. Propane was used as the fuel source at \$2.00 per gallon, which matched what the facility spent on fuel at that time. Infiltration through gaps was set to 0.5 air exchanges per hour to simulate the well-sealed structure. A heating efficiency of 52% was used to simulate older unit heaters with below bench heat distribution tubes. A winter production period of 3 months was simulated covering 1 Dec. through 28 Feb. (total of 90 d). This period matched the period of active $CO_2$ control during the experiment.

Lettuce mass and leaf number were averaged for each treatment and standard errors were calculated. A Student's paired *t* test of means was used to determine significance using statistical software (Statistix version 9.0; Analytical Software, Tallahassee, FL).

## Results and discussion

For the 3-month experimental period, the temperature was maintained to within 1 °F of set points in each greenhouse. This variation was low and compares favorably to research-quality greenhouses. During the experimental period, there was no active ventilation to the outside; outside temperatures were cold from December to February (below freezing average temperature). Heaters and passive cooling were the primary methods for temperature control. It is important to note that no measurements were made during the night. $CO_2$ in the control greenhouse was between 200 and 300 ppm on sunny or partly sunny days and always at least 100 ppm lower during the day than the cooler greenhouse receiving supplemental $CO_2$. Given the conditions during this experiment, it is necessary to determine if this decrease in $CO_2$ concentration would be reasonable to expect. A simple model driven by light availability can help predict how quickly this drawdown can occur (Table 2; Monteith, 1977; Volk et al., 1995). Using some typical values for the model in this greenhouse (Table 2), it can be calculated that after 1 h, 9.0 mol $CO_2$ were removed with photosynthesis leaving only 15.0 mol of $CO_2$ remaining or 258 ppm $CO_2$ if no ventilation, leakage, or $CO_2$ supplementation occurs. Drawdown would be slower if ambient light was reduced or fewer plants were present and faster with more or larger plants present, perhaps later in the production cycle. The low $CO_2$ measured on sunny days is a clear indication that there was little air leakage or mixing between inside and outside the

### Units

| To convert U.S. to SI, multiply by | U.S. unit | SI unit | To convert SI to U.S., multiply by |
|---|---|---|---|
| 0.3048 | ft | m | 3.2808 |
| 0.0929 | $ft^2$ | $m^2$ | 10.7639 |
| 0.0283 | $ft^3$ | $m^3$ | 35.3147 |
| 3.7854 | gal | L | 0.2642 |
| 2.54 | inch(es) | cm | 0.3937 |
| 0.4536 | lb | kg | 2.2046 |
| 28.3495 | oz | g | 0.0353 |
| 1 | ppm | $\mu mol \cdot mol^{-1}$ | 1 |
| (°F – 32) ÷ 1.8 | °F | °C | (1.8 × °C) + 32 |

**Table 1. Costs of fuel and carbon (C) consumed during the 90-d winter production period for the control and carbon dioxide ($CO_2$)-elevated greenhouses that were maintained at a constant 65 or 62 °F (18.3 or 16.7 °C), respectively. The 90-d period spanned from 1 Dec. to 28 Feb.**

| Treatment | Cost of propane ($) | C from propane (lb)$^z$ | C from elevated $CO_2$ (lb) | Cost of elevated $CO_2$ ($) | Total C from propane and $CO_2$ (lb) | Cost from propane and $CO_2$ ($) |
|---|---|---|---|---|---|---|
| Uncontrolled $CO_2$, 65 °F | 15,147 | 92,169 | 0 | 0 | 92,169 | 15,147 |
| Elevated $CO_2$, 62 °F | 13,871 | 84,405 | 1200 | 931 | 85,605 | 14,802 |

$^z$1 lb = 0.4536 kg.

**Table 2. Model parameters used in calculations for carbon dioxide ($CO_2$) reduction within a greenhouse in 1 h. This is a light-driven model that uses measurements or assumptions about how that light is absorbed, used photosynthetically, and the fixed carbon is subsequently respired in carbon use efficiency. Combined with measurements of greenhouse area, volume, and interior $CO_2$ concentration, an estimate of the decrease in $CO_2$ because of photosynthesis can be made in a time step (1 h in this example).**

| Term$^z$ | Typical range | Values used in calculations | Citation(s) |
|---|---|---|---|
| Available light ($mol \cdot m^{-2} \cdot h^{-1}$) | 0–7.2 | 2.7 | |
| Light entering greenhouse (%) | 30–70 | 50 | Korczynski et al. 2002 |
| Absorption (%) | 0–100 | 50 | Goudriaan and Monteith, 1990 |
| Photosynthetic efficiency (%) | 0–12.5 | 0.0415 | Lal and Edwards, 1995; Long, 1991; Thornley and Johnson, 1990 |
| Carbon use efficiency (%) | 0–70 | 65 | Frantz et al. 2004 |
| Greenhouse area ($ft^2$) | 0–∞ | 5,336 | |
| Greenhouse volume ($ft^3$) | 0–∞ | 50,926 | |
| Starting $CO_2$ concentration (ppm) | 0–2000 | 400 | |

$^z$1 $ft^2$ = 0.0929 $m^2$, 1 $ft^3$ = 0.0283 $m^3$, 1 ppm = 1 $\mu mol \cdot mol^{-1}$.

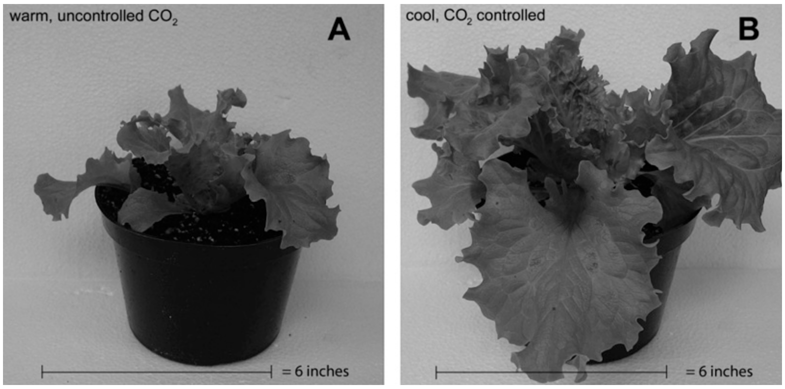

**Fig. 1. Lettuce plants after 45 d of growth in greenhouse maintained at 65 °F [18.3 °C (warm)] with no carbon dioxide ($CO_2$) control (A) or in a greenhouse maintained at 62 °F [16.7 °C (cool)] with a $CO_2$ set point of 500 ppm (B). $CO_2$ in the warmer greenhouse was consistently 100 ppm lower than the cooler greenhouse and on sunny days, up to 300 ppm lower; 1 ppm = 1 $\mu mol \cdot mol^{-1}$, 1 inch = 2.54 cm.**

greenhouse. Similarly, $CO_2$ addition was more frequent on sunny days, based on the audible operation of the solenoid indicating that plants were actively drawing down the $CO_2$ available at those times.

Forty-five days after planting, harvested lettuce plants were larger in the cooler, $CO_2$-controlled house (Fig. 1). Dry weight was substantially greater in plants from the cooler, $CO_2$-controlled house (Fig. 2A; $P < 0.0001$). Jie and Kong (1998) documented no change in plant dry weight for lettuce over a range of temperatures from 59 to 77 °F when grown in ambient $CO_2$ conditions. Thompson et al. (1998) found increased lettuce dry weight per plant from 62.6 to 75.2 °F because of more, larger leaves in warmer conditions. In the current study, the cooler, $CO_2$-supplemented lettuce plants averaged 2.8 leaves more per plant than the warmer, uncontrolled $CO_2$ plants (Fig. 2B; $P < 0.0001$). This suggests that development in the cooler environment, when it was predicted to decrease, was compensated by higher $CO_2$. Lettuce growers are not as concerned about leaf count or development as floriculture producers, who rely on days to first flower to meet their market demands. It is unknown if leaf development rate in lettuce would correspond to days to flower in ornamental crops. Even though the lettuce was harvested, $CO_2$ additions continued for an additional 45 d to allow the commercial grower to continue producing vegetative cuttings from stock plants in consistent environments.

Growers may encounter sink limitation when using supplemental $CO_2$. This occurs when the assimilated C no longer can be used in the construction of new roots, leaves, or fruit, so photosynthesis is downregulated making plants appear to no longer "benefit" from supplemental $CO_2$ (Arp, 1991). The plants grown in these greenhouses were vegetative. Large pots were used for the lettuce to reduce the possibility of encountering a sink limitation over the course of the 45-d growth period. Production in smaller containers (i.e., plug trays) or longer production of nonfruiting/nonharvested crops may encounter sink limitations and therefore not benefit from supplemental $CO_2$ (Arp, 1991). In some of those cases, then, slower development and growth because of lower temperatures is not an issue.

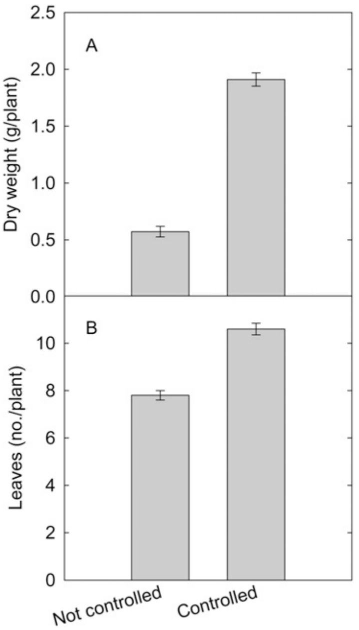

**Fig. 2. Average dry weight (A) and leaves per plant (B) of lettuce plants harvested after 45 d from greenhouses maintained either at 65 °F (18.3 °C) with no carbon dioxide ($CO_2$) control (not controlled) or in a greenhouse maintained at 62 °F (16.7 °C) with a $CO_2$ set point of 500 ppm (controlled). Averages of each are significantly different ($P < 0.0001$) based on Student's paired *t* test of means. Error bars represent +/− 1 SE of mean; 1 g = 0.0353 oz, 1 ppm = 1 $\mu mol \cdot mol^{-1}$.**

The differences between the control greenhouse and cooler greenhouse receiving supplemental $CO_2$ in cost and C consumed from heating and supplemental C are reported in Table 1. The cost of propane was nearly $1300 (8.4%) more, and the control greenhouse consumed over 7000 lb more C than the cooler greenhouse. This difference is consistent with widespread "rules of thumb" that ≈3% of costs can be saved for every 1 °F that temperature is reduced. This rule of thumb, however useful, ignores potential productivity and development losses at cooler temperatures (Lopez and Runkle, 2004). There was a total of 1200 lb of C consumed from supplemental $CO_2$. Even when that was included, the cooler, $CO_2$-controlled greenhouse consumed less C from combustion and supplemental $CO_2$ than the warmer, unsupplemented house. Liquid $CO_2$ is expensive, as is the cost of monitoring and controlling $CO_2$ injection. When these costs were combined, including the accompanying instrumentation, the cooler, $CO_2$-controlled greenhouse was less expensive to operate than the warmer, uncontrolled $CO_2$ greenhouse. This cost difference would be greater if similar sized plants were produced because it would have taken longer for the warmer, control house to produce lettuce of equal size as the $CO_2$-controlled house.

The entire cost of the $CO_2$ controller, solenoid, and piping was factored into these costs even though their lifetime is far greater than a 3-month production system. Most commercial facilities would factor those costs over the lifetime of the materials and equipment. Additionally, liquid $CO_2$ from a laboratory supply company in small batches was used, which artificially increased the cost. Given differences in how different facilities calculate amortization of costs and variability in cost of $CO_2$, the full costs are presented herein as a worst-case scenario. Any changes in those costs per unit would further favor the cooler greenhouse receiving supplemental $CO_2$. For more recent cost estimates for the use of $CO_2$ as either liquid form or from combustion, see Blom et al. (2009). Liquid $CO_2$ was also used as a way to ensure no ethylene problems were encountered as can occur in incomplete combustion from $CO_2$ generators. Cleaning ethylene and other off-gases from the combustion used for heating the greenhouse under normal operating conditions would open up the possibility of using the $CO_2$ generated during this step (Armor, 1992; Critten and Bailey, 2002). This would enhance C conservation further and potentially provide an on-site source for $CO_2$ supplementation.

In this study, elevated $CO_2$ (500 ppm) was compared with below "ambient $CO_2$" (typically 200 to 300 ppm on sunny days within the greenhouse). It is not known if such a large benefit (plant size and leaf number) would be observed if the comparison was made between plants grown at 400 ppm (close to "ambient") and a set point of 700 to 800 ppm at two different temperatures. Certainly, growth differences observed were due in part to the control plants grown nearly at their $CO_2$ compensation point during sunny days making their growth negligible on those days. Their growth would have improved considerably even if they had been grown in an environment with "ambient" $CO_2$ conditions (i.e., 400 ppm $CO_2$). Still, in well-sealed greenhouses with no active ventilation, $CO_2$ is likely to be below ambient, particularly in partly cloudy or sunny conditions.

How much would leakage or ventilation help control $CO_2$ concentration within these greenhouses? The following equation, similar to exponential decay equations, describes the amount of original air remaining in a volume given a flow into that volume over a period of time: percent volume remaining = $e^{-[(\text{flow}/\text{volume}) \times \text{time}]} \times 100$. To use the equation for a greenhouse, the volume of the greenhouse and the air infiltration must be known. Greenhouse air infiltration is typically reported as "air exchanges per hour" and is a relative volume specific to that greenhouse. For example, if a greenhouse has a 50,000 $ft^3$ volume, an air infiltration rate of 1 means that 50,000 $ft^3$ of air flows into that greenhouse (or out) per hour. A tight, newly constructed, well-sealed greenhouse often has an air exchange rate of 0.5 to 1.0, while a poorly sealed or well-ventilated greenhouse may have an air exchange rate of 5.0 or more (Aldrich and Bartok, 1994).

Assuming the same environmental conditions and greenhouse as above, but an air exchange rate of 5.0 air exchanges per hour, the drawdown is less severe but still significant. After one hour, the $CO_2$ concentration is calculated to be 373 ppm. In a well-constructed, well-insulated greenhouse (0.5 air exchanges per hour), the $CO_2$ concentration is calculated to be just under 290 ppm. In other words, ventilation would help alleviate $CO_2$ drawdown, but even in well-ventilated greenhouses, $CO_2$ would still be less than outside conditions. Using Virtual Grower software (Frantz et al., 2010) to simulate the cost of heating between a well-sealed greenhouse as described above to a well-ventilated greenhouse with 5.0 air exchanges per hour, the costs of heating in Toledo, OH for December through February rises from $15,147 to $27,436. Clearly, it is more expensive to ventilate for $CO_2$ control than add supplemental $CO_2$.

These results illustrate that it is possible to save money, heating energy, and carbon from heating in certain situations where supplemental $CO_2$ is used. The use of $CO_2$ enrichment should, therefore, be considered in sustainable systems when its use can counteract the plant growth and development effects brought on by lowered temperatures. More work is needed, however, that development can accelerate in supplemental $CO_2$ environments compared with subambient $CO_2$ environments. Further, it would be of interest to determine if sink limitations are encountered in containerized plant production systems when supplemental $CO_2$ is used in longer term crops.

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