Carbon Dioxide Enrichment of High-value Crops under Tunnel Culture

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Abstract. The feasibility of field-scale CO₂ enrichment of vegetable crops grown under tunnel culture was studied with cucumber (*Cucumis sativus* L. cv. Dasher II), summer squash (*Cucurbita pepo* L. cv. Gold Bar), and tomato (*Lycopersicon esculentum* Mill. cv. Bingo) grown under polyethylene tunnels. The drip irrigation system was used to uniformly deliver a CO₂-enriched air stream independent of irrigation. Carbon dioxide was maintained between 700 and 1000 µl·liter⁻¹ during daylight hours. Enrichment began immediately after crop establishment and continued for ≈4 weeks. At the end of the treatment phase, enrichment had significantly increased plant dry weight in the 2 years of tests. This growth advantage continued through harvest, with enriched cucumber, squash, and tomato plots yielding 30%, 20%, and 32% more fruit, respectively, in 1989. In 1990, cucumber and squash yields were increased 20%, and 16%, respectively. As performed, the expense of CO₂ enrichment represented less than a 10% increase in total preharvest costs. A similar test was conducted on fall-planted strawberries (*Fragaria* × *ananassa* Duch. cvs. Irvine and Chandler). Carbon dioxide enrichment under tunnel culture modestly increased 'Irvine' yields but did not affect 'Chandler'.

Carbon dioxide enrichment of greenhouse crops has been a standard commercial practice for many years. Vegetable crops such as tomato, cucumber, and lettuce respond positively to greenhouse enrichment; yield increases of 20% to 40% are common (Hadley and Livermore, 1989; Kimball, 1986; Peet and Willits, 1987; Slack, 1986). Carbon dioxide enrichment for such crops under field conditions has been the subject of considerable speculation. The concept has generally been dismissed as impractical due to problems in uniformity of distribution and rapid dispersal of applied CO₂ by wind movement.

The use of polyethylene-covered growing tunnels has in recent years become a relatively common cultural practice for the production of high-value crops; the substantial cost of this technique can be offset by increased yield and a market premium for earlier production. The use of polyethylene tunnels provides a relatively static atmosphere around the crop, improving the practicality of CO₂ enrichment on a field basis. Hadley and Livermore (1989) reported increased growth rate and earlier maturity of crisphead lettuce (*Lactuca sativa* L.) when small, air-inflated field enclosures were enriched to approximately three times normal atmospheric CO₂ concentration. The applicability of their study was limited in that their enclosures were in essence small greenhouses, and their CO₂ distribution system consisted of delivering pure CO₂ through a perforated plastic pipe.

A more practical solution to the issue of even distribution would be to deliver CO₂ through drip irrigation lines (Wittwer, 1979). Wittwer's idea was to deliver CO₂ in the irrigation water stream. Nakayama and Bucks (1980) documented crop response under field conditions with this technique, although plant response probably was not due directly to enhancement of atmospheric CO₂ concentration; root-zone delivery of CO₂ has been shown to induce effects beyond enhancement of photosynthesis (Arteca et al., 1979; Govindarajan and Poovaiah, 1982; Mauney and Hendrix, 1988). Carbon dioxide delivery in irrigation water is of limited usefulness for atmospheric enrichment, since ideal timing and application amount for each are

not compatible. However, using a drip irrigation system for delivery of gaseous CO₂ independent of water application could be a workable field technique.

This study was undertaken to document agronomic response and economic feasibility of CO₂ enrichment of high-value crops grown under conventional polyethylene tunnels, using drip irrigation lines as the distribution system for CO₂.

Materials and Methods

Field studies were conducted during Spring 1989 and 1990 at the Univ. of California Agricultural Experiment Station at Riverside, and during Fall 1989 at the Univ. of California South Coast Field Station in Irvine. Soils were Buren fine sandy loam (Riverside) and San Emigdio sandy loam (Irvine). In Spring 1989, the Riverside site was fumigated with a methyl bromide/chloropicrin mixture. A broadcast application of 55 kg N and 30 kg P was made before the formation of raised beds on 1.5-m centers. A single drip irrigation line (Turbo-tape, 20-cm emitter spacing, T-Systems, San Diego, Calif.) was buried 10 cm deep in the center of each bed.

A CO₂ injection system was constructed that used the buried drip irrigation lines to deliver a CO₂-enriched air stream uniformly down the length of each row. The system contained a vacuum motor whose positive pressure port provided an air flow at ≈7 kPa static pressure. Bottled CO₂ was metered and blended into this flow to provide enrichment to a concentration of ≈5% v/v. The rate of delivery of the enriched air, ≈0.3 liter·min⁻¹·m⁻¹ drip tape, was sufficiently slow to allow adequate mixing of this potentially toxic CO₂ concentration with the tunnel atmosphere.

The CO₂ level in the enriched tunnel atmosphere was monitored by a nondispersive infrared CO₂ analyzer originally designed for greenhouse use (Model 2044, Valtronics, Concord, Calif.). The monitor's switching capabilities operated the delivery system, delivering enrichment when tunnel atmosphere CO₂ concentration fell below 700 µl·liter⁻¹ stopping flow at 1000 µl·liter⁻¹. A sampling manifold was constructed that drew a composite air sample from three enriched tunnels 15 cm above the soil surface. The overall control of the system, which operated on 110-VAC current, was a time clock that limited hours of operation to 0800 to 1500 hr. The delivery of enriched air was accomplished independently of irrigation, which was ap-

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plied as needed after the daily enrichment period. We also periodically monitored CO₂ concentration in nonenriched tunnels. The analyzer was recalibrated twice during the enrichment period using standardized gas mixtures.

On 1 Mar. 1989, the experimental area was planted with seed of 'Dasher II' cucumber and 'Gold Bar' squash. Conventional growing tunnels were constructed over the seeded rows; the tunnels consisted of wire hoops covered by single sheets of 30 μ m clear, perforated polyethylene. The perforations, which comprised 1% of the surface area, were needed to prevent lethal temperature buildup should unseasonably warm weather occur. As configured in this study, the tunnels had a cross-sectional area of 0.3 m². On 10 Mar., 4-week-old 'Bingo' tomato transplants were planted and covered by tunnels. The design for each crop was a randomized complete block, with five replications. Individual plots were 10 m (cucumber, squash) or 6 m (tomato) long. In-row plant spacing was 30 cm (cucumber) or 45 cm (tomato, squash). The CO₂-enrichment treatment began on 13 Mar., at which time the seeded crops were at the first true-leaf stage, and continued until 7 Apr., when hot weather forced ventilation of the tunnels.

Upon termination of the enrichment, two representative plants from each cucumber and squash plot were harvested and oven-dried at 65C for dry weight determination. Routine cultural practices were followed for the balance of the cropping season. Cucumbers were harvested eight times from 21 Apr.–18 May, squash five times from 1–29 May. Breaker-stage tomatoes were harvested 16 and 26 June, followed by a harvest of all remaining fruit on 3 July.

This study was repeated at Riverside during Spring 1990. The protocol was the same as previously described with the following modifications. The drip irrigation lines through which the CO₂-enriched air stream was delivered were placed on the soil surface rather than underground. A different CO₂ monitor was used (Model APBA-250E, Horiba Instruments, Irvine.) Metam-sodium at 230 liters a.i./ha applied preplant in irrigation water provided weed control. The design was a randomized complete block with four 6-m plots.

Cucumber and squash (same cultivars as 1989) were seeded on 27 Feb. and immediately covered with tunnels. Carbon dioxide enrichment began 20 Mar., at the two true-leaf stage. Enrichment was applied daily, as previously described, until 12 Apr. (squash) and 20 Apr. (cucumber), the earlier termination on the squash necessitated by its larger size and the restricted area within the tunnel. Plant dry weights were again taken at the termination of enrichment. Yields were taken weekly on both crops from 3–24 May.

This tunnel enrichment procedure was also evaluated on fall-planted strawberries at Irvine in 1989. Raised soil beds on 1.7-m centers were prepared and fertilized by banded application of 70 kg N and 40 kg P/ha. The beds were mulched with 30 μ m clear polyethylene. Metam-sodium at 230 liters a.i./ha was applied in water through buried drip irrigation lines to control weeds and soil-borne pathogens. Crowns of 'Irvine' and 'Chandler' strawberries were planted in a four-row-per-bed configuration at a density of 100,000/ha on 19 Oct. The design for each cultivar was a randomized complete block with four replications. Individual plots contained 50 plants. Since the use of tunnels is not an established practice for Southern California strawberry production, a conventional (nonenriched, nontunneled) control was included in addition to the nonenriched tunnel control.

After a 3-week establishment period, polyethylene tunnels

were constructed. Carbon dioxide enrichment began on 14 Nov., with delivery through drip lines on the soil surface. Enrichment was delivered from 0800 to 1600 HR daily, as previously described. With the exception of two windy periods when enrichment was suspended, the treatment continued until 20 Dec. for 'Irvine' and Jan. 1990 for 'Chandler'. Termination of enrichment corresponded to the initiation of harvest of the cultivars.

Upon termination of enrichment, tunnels were removed and routine commercial management practices instituted. Additional N was applied weekly at 12 kg·ha⁻¹ through drip injection. Weekly harvests were taken until 15 May 1990.

Results and Discussion

The CO₂ injection system worked well under calm conditions, maintaining CO₂ in the target range. However, in wind velocities >5 m·s⁻¹, the delivery system maintained 700 μ l-liter⁻¹ with difficulty. Enrichment was halted on several occasions due to extreme winds. The perforated tunnels allowed sufficient air exchange to maintain CO₂ concentration in nonenriched tunnels near ambient levels. Tunnel air temperatures were substantially higher in 1989, with a daily maximum of 41C compared with 37C in 1990.

Enrichment of the tunnel atmosphere increased plant dry weight of cucumber 57% and 32%, and squash 69% and 70% for 1989 and 1990, respectively (Table 1). At the end of the treatment period, CO₂-enriched plants appeared to be more vigorous; cucumber plants were also more advanced with respect to bloom and fruit set. Enriched tomato and strawberry plants also showed enhanced growth, but plant dry weights were not determined.

Carbon dioxide enrichment significantly increased total marketable yield of cucumber and squash in both years, with the magnitude of increase greater in 1989 (Table 1). There were no differences in cucumber quality between treatments. Field labor constraints restricted squash harvests to weekly intervals, so many fruit were larger than commercially desirable; the only quality classification of squash was marketability, irrespective of fruit size. Tomato also showed significantly enhanced productivity, with enrichment increasing marketable yield by 32% (Table 2). Mean fruit size also was increased.

Enrichment resulted in earlier cucumber harvest, with harvest of enriched plots beginning 5 to 7 days before nonenriched plots in both years. Differences in early yield, defined as yield in the

Table 1. Effect of CO₂ enrichment on cucumber and squash production.

Crop	Year	Treatment	Plant dry wt (g)	Marketable yield (kg/plot)	
				Early	Total
Cucumber	1989	Enriched tunnel	22.3	12.59	46.9
		Tunnel control	14.2	4.87	36.1
	1990	Enriched tunnel	31.2	11.45	29.3
		Tunnel control	23.5	8.74	24.5
Squash	1989	Enriched tunnel	70.2	5.38	51.0
		Tunnel control	41.6	5.45	42.6
	1990	Enriched tunnel	31.3	5.84	29.8
		Tunnel control	18.4	4.31	25.8

NS, *, ** Nonsignificant and significant at $P = 0.05$ and 0.01 , respectively.

Table 2. Effect of CO₂ enrichment on tomato production under tunnels, 1989.

Enrichment	Marketable yield (kg/plot)		Fruit size distribution (%)	
	Early	T o t a l	D i a m	
			< 7 . 5 c m	>7.5 c m
Yes	11.46	64.0	23	77
No	12.91	47.9	35	65

^{ns}, * Nonsignificant or significant at $P = 0.05$.

Table 3. Effect of tunnel culture and CO₂ enrichment on strawberry production.

Treatment	Marketable yield (kg/plot)	
	Irvine	Chandler
Enriched tunnel (ET)	27.3	32.8
Tunnel control (TC)	25.9	29.1
Conventional control (CC)	24.4	31.1
Orthogonal comparisons		
Significance		
ET vs. TC	0.06	0.09
ET vs. CC	0.01	N S

^{ns} Nonsignificant at $P = 0.10$.

first half of the harvest period, was significant only in 1989. Extremely high tunnel temperatures in 1989 (maximum >45°C) caused abortion of early fruits in squash and tomato, delaying harvest and obscuring treatment effects on earliness. In 1990, enrichment had a negligible effect on earliness in squash.

Both strawberry cultivars showed a marginal yield increase due to enrichment compared with the tunnel, nonenriched treatment (Table 3). Compared with conventionally grown (nontunnel) plants, enrichment under tunnel culture significantly improved productivity of 'Irvine', but not of 'Chandler'. Mean fruit size was unaffected by treatment (≈ 19 g for 'Irvine', ≈ 17 g for 'Chandler'). Enrichment enhanced yield for the first 4 weeks of the harvest season for both cultivars, but these early harvests accounted for <5% of seasonal total yield.

Carbon dioxide usage amounted to ≈ 115 and $95 \text{ kg} \cdot \text{ha}^{-1} \cdot \text{day}^{-1}$ for the Spring 1989 and 1990 tests, respectively. Daily usage was considerably higher for the strawberry test, $170 \text{ kg} \cdot \text{ha}^{-1}$, reflecting longer hours of operation and more wind-induced loss.

Enrichment of cucurbits and tomato resulted in growth enhancement and yield increases similar to those reported in greenhouse enrichment studies. In reviewing numerous previous studies, Kimball (1986) found a mean yield increase of 26% for cucumber due to CO₂ enrichment. Calvert and Slack (1975) reported a similar response in greenhouse-grown tomato. The advanced maturity of enriched cucumber plots was also consistent with reports on other crops (Goldsberry, 1988; Hadley and Livermore, 1989; Milhet and Costes, 1975).

The major difference between traditional greenhouse-enrichment regimes and the current study is that greenhouse enrichment typically takes place throughout the cropping season, whereas 'the tunnel enrichment was confined to early season growth. The success of tunnel enrichment as conducted here may be partially attributable to enrichment throughout the day; greenhouse enrichment is often interrupted by venting for temperature control. Slack (1986) reported that maximum benefit occurs when enrichment is applied for long periods without interruption.

In cucumber and squash, there were considerable differences in overall productivity and response to enrichment between years. Slower plant development and lower yields in 1990 may have been related to cooler seasonal temperatures and less-effective soil fumigation than in 1989.

Another difference of potential importance was the placement of the drip irrigation lines, which were buried in 1989 and on the soil surface in 1990. Root-zone application of CO₂ has been shown to have significant stimulator effects on a diversity of crops, including *Citrus* (Labanauskas, et al., 1971), cotton (*Gossypium hirsutum* L.) (Mauney and Hendrix, 1988), eggplant (*Solanum melongena* L.) (Baron and Gorski, 1986), potato (*Solanum tuberosum* L.) (Arteca et al, 1979) and wheat (*Triticum aestivum* L.) (Nakayama and Bucks, 1980). Beyond actual root fixation of soil-applied CO₂ (Arteca and Poovaiah, 1982; Baron and Gorski, 1986) other mechanisms of action have been suggested, including inhibition of ethylene biosynthesis and action (Govindarajan and Poovaiah, 1982) and alteration of endogenous hormone levels (Arteca et al., 1980). The stronger response to enrichment in 1989 may have been related to one or more of these factors acting in concert with atmospheric enrichment.

Despite obvious stimulation of early season plant growth, the effects of tunnel culture and enrichment on strawberry production were nominal. This marginal response may be related to the complex physiology of flowering in strawberry; daylength, temperature, varietal characteristics, environment of crown production, etc. all influence the timing and number of flower buds initiated. The use of tunnels, as deployed in this study, radically increased air temperature, which may have modified the balance of vegetative and reproductive growth. Also, because peak harvest was ≈ 4 months after the cessation of enrichment, treatment effects might be expected to be minimized.

From an engineering standpoint, delivery of a CO₂-enriched air stream through conventional drip lines functioned well. In the short plot lengths employed, relatively uniform distribution was achieved however, pressure measurements on a 50-m length of line charged by the pumping system showed minimal pressure drop, indicating that the technique is feasible on a larger scale. By injecting an enriched air stream instead of pure CO₂, the effects of any nonuniformity of distribution were minimized. The adaptation of this technique to field-scale usage would require a different mechanical scheme than we used to pressurize the system. Also, brands of drip tubing may differ significantly in air flow characteristics, so that careful evaluation would be required.

As performed in this study, CO₂ enrichment could be an economically justifiable practice for the production of cucurbits and tomatoes using tunnel culture. Although expenses vary widely among growers in different production areas, preharvest variable costs for these crops under tunnel culture and drip irrigation but without CO₂ enrichment, are at least \$2500/ha-1; when fixed costs are added, the total commonly exceeds \$3500/ha⁻¹. Carbon dioxide in bulk containers commonly available in North America cost approximately \$0.08 to \$0.12/kg, depending on quantity used and proximity to a supply source. At the usage rates in the spring tests, seasonal CO₂ costs would approximate \$200 to \$300/ha. In areas where the weather would permit the use of nonperforated tunnel covers, CO₂ usage and expense could be reduced considerably. Carbon dioxide monitors designed for greenhouse use are available for approximately \$1000. Expense of the delivery system would vary, depending on the level of sophistication and the scale of production.

The use of this technique would be more difficult to justify economically for strawberry production. Since the use of tunnels is not a common practice for this crop, their considerable cost, plus expenses related to enrichment, would have to be recovered in higher yields or earliness; based on the marginal crop responses we obtained, that is unlikely.

The source of CO₂ used in these studies was industrial bottled CO₂. This product is captured as a byproduct of industrial processes such as fertilizer manufacturing and food processing. The use of this product in agriculture represents a recycling of CO₂ that would otherwise be vented directly to the atmosphere.

In summary, a technique for CO₂ enrichment of polyethylene growing tunnels under field conditions was tested. Yields of cucumber, squash, and tomato were significantly increased. The technique, which used existing drip irrigation lines to uniformly distribute applied CO₂, appeared to be an economically viable practice. The enrichment used CO₂ recycled from unrelated industrial processes and as such was an environmentally sensitive production technique.

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