Reviews

Soil, Plant, and Canopy Responses To Carbonated Irrigation Water

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Summary. Scientists have sought to stimulate plant growth using carbonated irrigation water for more than 100 years. The mechanisms by which carbonated water may increase plant productivity and the influence of environmental and cultural growing conditions on those mechanisms are not completely understood. Several greenhouse and field studies have demonstrated that carbonated irrigation water can increase crop yield significantly while others have shown that carbonated irrigation water does not influence plant productivity. It is unlikely that

carbonated irrigation water will be recommended commercially until the conditions are delineated under which a positive and economically advantageous growth response is ensured.

Several mechanisms that may influence a growth response to carbonated water have been identified. Carbon dioxide reduces water pH and may reduce soil pH, resulting in an increased availability of several crop nutrients. Carbonated irrigation water also increases the soil-air CO₂ concentration. This may enhance root growth by reducing ethylene inhibition and may stimulate beneficial bacteria. Carbon dioxide also can be absorbed directly through the plant roots and fixed in photosynthesis, although direct absorption is probably not a major contributing source to increased productivity. However, carbonated irrigation water can increase the rate of photosynthesis through atmospheric enrichment. It also may influence plant hormone and enzyme balances, which may enhance productivity. A growth response to carbonated irrigation water is likely due to a combination of factors, and it is most likely to be observed where soil and irrigation water pH are high, polyethylene mulch and drip irrigation are used, and irrigation is frequent and of long duration.

Several researchers reported that carbonated irrigation water increased plant yield (Mauney and Hendrix, 1988; Nakayama and Bucks, 1980; Novero et al., 1991). Others found that carbonated irrigation water did not influence, or negatively influenced, crop yield (Hartz and Holt, 1991; Nakayama and Bucks, 1980; Stoffella et al., 1995; Storlie, 1992). Contro-

versy exists over the alleged benefits of this practice due to the variety of reported results and the lack of consensus about mechanisms by which carbonated water might increase plant productivity. In this paper we review the potential mechanisms of increased plant productivity and outline the environmental and cultural conditions under which a plant response is most likely.

Mechanisms of increasing plant productivity

Mechanism 1—Increased nutrient uptake. One potential benefit of carbonated irrigation water is related to soil nutrient availability. Adding CO₂ to water acidifies the solution. Adding carbonated water to soil may cause soil pH to decline temporarily. In high-pH soils, this response brings soils into the desirable pH range for nutrient availability. In acidic soils, this response could cause aluminum toxicity or limit the availability of essential plant nutrients. Reducing soil pH also may increase the activity of certain beneficial microorganisms (Baker, 1988).

Novero et al. (1991) reported the results of a Colorado study in which the concentration of Zn in the leaves of field-grown tomatoes receiving carbonated irrigation water was significantly higher than in the control. In addition, they concluded that the uptake of all measured nutrients increased because the yields of treatments receiving carbonated water were significantly higher, and that in no case were plant nutrient concentrations lower in treated plants. Total and marketable yields were 15.9% and 16.4% greater with CO₂-enriched water than the control, respectively. Novero et al. (1991) attributed increased nutrient uptake to increased nutrient availability caused by decreased soil pH. In one study, soil pH measured during irrigation was 6.8 in the carbonated water treatment and 7.7 in the control. In another study, soil pH measured immediately after irrigation ranged from 5.9 to 6.2 in the carbonated water treatment and from 7.4 to 7.6 in the control. Where irrigation water was applied every sixth day, soil pH gradually rose from 5.9 immediately after irrigation to 7.1 on the day before the next irrigation. The optimum pH for most cultivated plants ranges from 5.0 to 7.0 (Spurway, 1941).

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Mauney and Hendrix (1988) reported that Zn and Mn concentrations were significantly higher in cotton plants treated with carbonated irrigation water. They attributed boll yield increases of 70% and 53% and a carbon exchange rate increase of 38% to higher uptake of these minerals, suggesting that a more robust photosynthetic apparatus resulted from enhanced mineral uptake. In their Arizona greenhouse study, soil pH decreased from 8.0 to 6.5 where carbonated water was applied. Mauney and Hendrix noted that none of the carbon in lint samples was derived from the CO₂ in the irrigation water, suggesting that the increase in yield was not a result of root CO₂ absorption or aerial enrichment.

Recently, Basile et al. (1993) showed that soil Zn, Mn, Fe, Ca, and Mg mobilities were increased by carbonated water, which reduced the pH of a clay loam soil packed within leaching columns from 7.5 to 6.0. In a related study, Arienzo et al. (1993) applied carbonated water to field-grown tomatoes in southern Italy and found that plant Zn, Mn, Ca, and Fe uptake were increased. The initial pH of the clay loam soil used in this study was 7.5. Bialczyk et al. (1994) also noted a similar effect in a study of tomatoes irrigated with carbonated water. The plant growth rate and uptake of N, K, and Ca of young tomato plants grown in nutrient solution with various HCO₃⁻ concentrations were increased compared with a control. However, they noted that the favorable effects may be obtained only under a limited range of HCO₃⁻ concentrations. Others also have noted that carbonated irrigation water affects the uptake of nutrients, although some studies have reported an increase in certain elements and a decrease in the uptake of others (Arteca et al., 1979; Kimball et al., 1986; Labanauskas et al., 1971; Stoffella et al., 1995). The number of scientific studies noting the effect of carbonated water on nutrient uptake suggests that this mechanism may play a major role in the response of plants to carbonated irrigation water.

Mechanism 2—Soil-air enrichment. The effect of carbonated irrigation water on the soil-air environment also may influence plant productivity. Novero et al. (1991) reported that soil-air CO₂ concentrations were increased where carbonated irrigation water was used along

with polyethylene mulch, and suggested that the CO₂-enriched soil atmosphere may have resulted in greater root development and greater nutrient uptake. Further, they found that a growth response was dependent on the presence of mulch, which they concluded reduced the escape rate of CO₂ from the soil.

Other researchers also have reported CO₂ enrichment of the soil atmosphere where polyethylene mulches were used (Hopen and Oebeker, 1975; Nakayama and Bucks, 1980; Sheldrake, 1963). Baron and Gorske (1986) grew eggplant in sealed pots containing a soilless mix and injected CO₂ into the growing medium at CO₂ concentrations ranging from 0.03% to 15%. At all injection rates, a significant increase in stem diameter was measured, whereas a significant increase in plant dry weight and leaf area occurred only during long day and warm temperature conditions. Based on these results, they concluded that part of the positive yield response of plants to polyethylene mulch is a result of soil-air CO₂ enrichment. Evidence that supports this conclusion appears in several studies that showed that CO₂ strongly counteracts the effect of ethylene inhibition and has a positive effect on root elongation (Govindarajan and Poovaiah, 1982; Jackson, 1985). Root-source CO₂ also may affect plant hormone and enzyme balances in other ways, influencing photosynthesis, respiration, and other plant processes (Arteca et al., 1980; Govindarajan and Poovaiah, 1982). Thus, increasing the soil-air CO₂ concentration also appears to play a key role in the response of plants to carbonated irrigation water.

Increasing the soil-air CO₂ concentration also may affect plant productivity through its impact on soil nitrification. The soil-air CO₂ concentration generally has been regarded as exceeding the biological demand of the nitrifying bacteria (Alexander, 1965). However, Buyanovsky and Wagner (1983) measured soil-air CO₂ concentrations in the field ranging from <1% to 7%. Clark (1968) measured soil nitrification over a range of soil-air CO₂ concentrations and found that the maximum nitrification rates occurred between soil-air CO₂ concentrations of 0.5% and 2.9%. Thus, soil-air CO₂ concentrations in the field may be sub- or supra-optimal for maxi-

mum nitrification, and carbonated irrigation water may affect nitrification either positively or negatively.

Mechanism 3—Direct absorption. Other research suggests that plants increase their growth rate by absorbing CO₂ from the irrigation water. Once absorbed, CO₂ is dissolved in the xylem sap or fixed as an organic acid and transported to the plant leaves where it is used as a carbon source in photosynthesis or as an energy source for other plant reactions (Arteca and Poovaiah, 1982a). Compounds fixed in the roots also may remain there and act as exchange ions or energy sources in the uptake and translocation of cations (Coker and Shubert, 1981; Jackson and Coleman, 1959).

Many studies have shown that plants are able to derive carbon from CO₂ contained in irrigation water. In a series of studies using a labeled carbon source, potatoes growing in nutrient solution absorbed CO₂ through their roots and transported it to the site of photosynthesis in the plant leaves (Arteca and Poovaiah, 1982a; Arteca et al., 1979). Substantial increases in tuberization, stolon length, the number of tubers per stolon, and overall plant dry weight were noted in plants that had their roots exposed for 12 h to a gas stream consisting of 45% CO₂. Root absorption of CO₂ also has been measured in tomato, eggplant, rice, peas, beans, oats, corn, wheat, and citrus (Arteca and Poovaiah, 1982b; Baron and Gorske, 1986; Bialczyk et al., 1994; Higuchi et al., 1984; Labanauskas et al., 1971; Schafer, 1988; Yurgalevitch and Janes, 1988). *Stylites andicola*, a land plant that does not possess stomata, derives nearly all of the carbon it fixes in photosynthesis from the CO₂ absorbed by its roots (Keeley et al., 1984).

It does not appear that for most plants the amount of CO₂ absorbed could substantially affect plant productivity. Schafer (1988) found that root absorption of HCO₃⁻ accounted for only 0.44% to 1.21% of the total carbon assimilated by wheat shoots. Mauney and Hendrix (1988) reported that cotton yields significantly increased in response to carbonated irrigation water, but that none of the carbon contained in the cotton lint was derived from carbonated irrigation water. Others have suggested that <5% of the CO₂ fixed by a plant could be

absorbed by the root system, and that increasing yields as a result of root absorption of carbonated irrigation water was unlikely (Skok et al., 1962; Stolwijk and Thimann, 1957). In contrast to these estimates, yield increases of 16.4% in tomato, 70% and 53% in cotton, and 20% in wheat have been reported (Mauney and Hendrix, 1988; Nakayama and Bucks, 1980; Novero et al., 1991). These data suggest that the influence of carbonated irrigation water on plant productivity can be attributed only partially to root CO_2 absorption.

Mechanism 4—Canopy enrichment. Carbonated irrigation water also may increase the CO_2 concentration of air in the plant canopy. Carbon dioxide dissolves slowly in water, where about 1% of it forms carbonic acid (Enoch and Olesen, 1993). Carbonic acid then is partially ionized, forming HCO_3^- and CO_3^{2-} . However, about 99% of CO_2 dissolved in water remains as dissolved CO_2 gas. A portion of the dissolved CO_2 may leave the soil solution as CO_2 gas. Novero et al. (1991) measured CO_2 concentration in the canopy of tomato plants supplied with carbonated irrigation water and grown using polyethylene mulch. They found elevated concentrations ranging from 2.2 to 4.1 times the ambient CO_2 concentration at a height of 1 cm above the soil surface during irrigation, and ranging from 1.2 to 1.5 times the ambient CO_2 concentration at a height of 15 cm above the soil surface. One hour after irrigation ended, concentrations ranging from 1.2 to 1.5 times the ambient concentration were measured at the 1-cm height. They concluded that aerial enhancement was partly responsible for the significant yield increases they measured.

Storlie (1992) measured canopy CO_2 concentrations in a closed bell pepper canopy while carbonated irrigation water was being applied with a drip irrigation system. Carbonated water enriched the air at the soil surface near the transplant hole 1.3 times the ambient level, but did not increase the concentration at locations 15, 30, or 45 cm above the soil surface. In this study, bell peppers were growing on polyethylene-mulched beds. Wind speed during testing ranged from 4 to 13 $\text{km}\cdot\text{h}^{-1}$. Sheldrake (1963) also measured increased canopy CO_2 concentrations where polyethylene mulch and drip irrigation were used. Noting a 4-

fold increase in CO_2 concentration at the soil surface, Sheldrake suggested that the growth response of plants to polyethylene mulch was due to atmospheric enrichment.

In addition to the reports cited earlier, several investigations reported nonsignificant or negative effects of carbonated irrigation water on plant productivity. These studies do not necessarily contradict the results of studies that reported a positive response to carbonated water. In New Jersey, Storlie (1992) reported that bell pepper yield was not influenced by carbonated irrigation water applied with a drip irrigation system and used along with polyethylene mulch. The irrigation water pH of 4.9 was reduced to 4.1 where CO_2 was injected at a saturating rate ($1.2 \text{ g}\cdot\text{liter}^{-1}$). Soil pH (initially 6.8) was influenced in an unpredictable manner and was affected by the untreated irrigation water as much as it was by the carbonated water. Pepper leaf macro- and microelement concentration differences among treatments were insignificant. Canopy enrichment with CO_2 was measured at the soil surface, but only during irrigations and for 30 min afterward. Storlie suggested that the lack of significant yield differences supports other research that has concluded that the influence of carbonated irrigation water on plants is largely due to enhanced mineral nutrition and is soil-pH dependent.

Hartz and Holt (1991) reported a similar experience growing cucumbers and tomatoes in California, where yields were not influenced, or were negatively influenced, by carbonated irrigation water. In these studies, irrigation water pH was decreased from 7.3 to 5.3 and soil pH was unpredictably affected. Tissue nutrient concentration differences among treatments were insignificant. Hartz and Holt suggested that the negative response that they measured at one site may have been due to polyethylene mulch, which they suspected increased the soil-air CO_2 content to supra-optimal levels.

Stoffella et al. (1995) also suspected that suppressing growing media pH to a sub-optimum level (from pH 6.90 to 5.65) affected their results in studies with citrus rootstock. In this study, carbonated water had the adverse effect of lower root weights and lower root Mn concentrations.

Environmental and cultural conditions under which a growth response to carbonated irrigation water is most likely

A set of environmental and cultural growing conditions under which a growth response to carbonated irrigation water is most likely can be suggested based on the results of the research reported in this review. Carbon dioxide reduces water pH and may reduce soil pH. Where soil pH is reduced from a supra-optimum level, nutrient uptake may be increased, suggesting that a growth response to carbonated water is likely where soil and water pH are higher than optimum.

The influence of CO_2 on soil and irrigation water pH and nutrient uptake enhancement suggests that geographic location may influence plant response to carbonated irrigation water. Conditions of high soil and irrigation water pH are common in many portions of the western United States. Thus, it is more likely that a crop response to carbonated irrigation water will be observed in the western than the eastern United States.

Drip irrigation and polyethylene mulch increase the soil-air and canopy CO_2 concentrations by providing a physical means of applying and containing carbonated irrigation water and gaseous CO_2 . Soil-air enrichment may increase root growth by reducing ethylene inhibition. Canopy enrichment increases photosynthesis and would have the greatest effect on aerial enrichment and photosynthesis where enrichment occurred during the entire photoperiod. Therefore, the influence of carbonated irrigation water on photosynthesis would be greatest in a region requiring frequent, long-duration irrigations. Again, these conditions are prevalent in the arid, western United States. In addition, the effect of carbonated water on canopy enrichment would be enhanced where wind speed is low and where the plant canopy is closed. These factors would reduce the effect of wind on CO_2 dilution.

The practice of irrigating with carbonated water has not been recommended commercially for several reasons. Research reports contain conflicting descriptions of plant responses to carbonated irrigation water. Reported yield increases in field studies

have been relatively small and may not justify the expenses associated with the practice. In addition, there remains a lack of understanding of the mechanisms of action and, more importantly, the influence of other plant and environmental factors on these mechanisms. The acceptance of carbonated irrigation water as a commercial production practice is unlikely until the plant and environmental conditions are delineated under which a positive and economically advantageous plant growth response is ensured.

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