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## Changes in Carbon Fixation, Tuberization, and Growth Induced by $CO_2$ Applications to the Root Zone of Potato Plants


Abstract. *The root systems of potato plants (*Solanum tuberosum *L. var. Russet Burbank) treated with $CO_2$ for 12 hours showed an increase in dry matter as early as 2 days after the treatment. When treated plants were allowed to grow for 3 to 6 weeks there was a substantial increase in tuberization. In addition, there was an increase in stolon length, number of tubers per stolon, and overall dry weight after the enrichment of the root zone with $CO_2$. Plants treated with $CO_2$ showed higher concentrations of malic and citric acids and of the cations $Mg^{2+}$ and $Ca^{2+}$. The effect of $CO_2$ was more dramatic when $CO_2$ was applied to the root zone than when it was applied to the shoots.*


Terrestrial plants have been credited with fixing about 25 billion metric tons of $CO_2$ per year (*1*). Atmospheric $CO_2$ concentrations appear to be limiting with respect to photosynthesis, because most $C_3$ plants (*2*) are capable of significantly greater rates of $CO_2$ fixation in the presence of higher concentrations of $CO_2$ than are present in ambient air. Carbon dioxide enrichment of the air increases yields of greenhouse-grown vegetable and flower crops (*3, 4*), but $CO_2$ enrichment of the air for field crops would not be practical. We have investigated the feasibility of increasing plant productivity by applying $CO_2$ to underground plant parts.

The response of plants to high concentrations of $CO_2$ depends on the species. The root growth of *Pisum sativum*, *Vicia faba*, *Phaseolus vulgaris*, and *Helianthus annua* were completely inhibited by high $CO_2$, whereas *Avena sativa* and *Hordeum vulgare* were unaffected (*5*). Potato plants are particularly well suited to $CO_2$ enrichment of the root zone because of their ability to tolerate high concentrations of $CO_2$ without the roots being damaged.

Potato plants were propagated by taking 1-cm plugs from the "eye" area of the tuber (*Solanum tuberosum* L. var. Russet Burbank). The plugs were arranged in holes bored into Styrofoam sheets and floated on water with continuous aeration in the dark for 2 weeks. When sprouts were 6 to 8 cm in length, they were detached from the plug and surface-sterilized in 10 percent sodium hypochlorite solution. The sterilized plants were transferred to 3-liter containers with full-strength Hoagland nutrient solution (*6*) and kept in a growth chamber under 16 hours of light (21.1°C) and 8 hours of darkness (15.6°C). Containers were covered with black polyethylene (5 mil in thickness) to keep light (which would inhibit tuberization) from reaching the bottom portion of the plant. Plants were grown for 3 weeks with continuous aeration. Nutrient solutions were changed weekly. After the 3-week growing period, uniform plants were selected for each treatment. The root zones of potato plants were aerated for varying time intervals with a gas stream that was 45 percent $CO_2$ with 21 percent $O_2$ and 34 percent $N_2$. Plant roots were immersed in aerated nutrient solution while stolons and tubers were suspended above the solution. Carbon dioxide enrichment was restricted to the root zones by isolating the roots in an airtight chamber with an outlet attached to a 25 percent sodium hydroxide trap for escaping $CO_2$, and the nutrient solution was maintained at a constant *p*H (5.5). All $CO_2$ experiments were conducted when the shoots were exposed to the light unless otherwise stated. We found that the 12-hour treatment period showed the best results with respect to dry matter increase and also the tuberization response.

Plants that had $CO_2$ applied to the roots showed a significant increase in shoot dry weight as early as 2 to 6 days after the treatment (Table 1). When plants were allowed to grow for 3 to 6 weeks after the $CO_2$ treatment, there was also a significant increase in the underground biomass (Fig. 1 and Tables 2 and 3). Three weeks after the 12-hour $CO_2$ treatment, stolons of the treated plants were not only longer than untreated controls, but also had multiple tubers as opposed to the single tubers per stolon typical of controls (Fig. 1 and Table 2).

Table 3 shows that root zone enrichment with $CO_2$ enhanced shoot weight. When potato shoots were treated with

Table 1. Effects of $CO_2$ enrichment of the root zone on dry matter content, organic acid, total chlorophyll, and mineral levels in nontuberizing potato plants. The $CO_2$ (45 percent $CO_2$, 21 percent $O_2$, and 34 percent $N_2$) was applied for 12 hours, at 2, 4, or 6 days before the plants were harvested. Control plants received ambient air. All plants were the same age at the time they were harvested. All values are expressed on a dry weight basis (± standard error).

| Days after $CO_2$ treatment | Plant dry weight (g) | Malic acid (mg/g) | | Citric acid (mg/g) | | Minerals* (total) | | | | | Total chlorophyll (mg/g) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Leaf | Root | Leaf | Root | $Ca^{2+}$ (mg/g) | $Mg^{2+}$ (mg/g) | $Mn^{2+}$ (μg/g) | $K^+$ (mg/g) | $Cl^-$ (μg/g) | |
| Control | 10.6 ± 2.3 | 9.2 ± 1.6 | 0.14 ± 0.005 | 4.3 ± 1.7 | 0.05 ± 0.003 | 43.7 ± 4.1 | 15.4 ± 0.25 | 2.5 ± 0.02 | 64.2 ± 1.6 | 928.4 ± 30.0 | 9.0 ± 0.46 |
| 2 | 14.9 ± 2.1 | 11.9 ± 0.63 | 1.4 ± 0.03 | 7.9 ± 2.3 | 0.29 ± 0.11 | 63.3 ± 4.9 | 12.5 ± 0.22 | 2.0 ± 0.01 | 61.0 ± 1.5 | 711.8 ± 26.5 | 9.7 ± 0.73 |
| 4 | 19.8 ± 4.5 | 15.2 ± 0.54 | 2.9 ± 0.86 | 10.9 ± 0.65 | 0.62 ± 0.28 | 76.8 ± 5.6 | 19.5 ± 0.28 | 2.1 ± 0.01 | 63.9 ± 1.5 | 681.3 ± 25.6 | 9.8 ± 0.95 |
| 6 | 25.8 ± 1.8 | 14.4 ± 0.29 | 3.9 ± 0.75 | 11.2 ± 0.38 | 1.1 ± 0.54 | 91.5 ± 6.2 | 18.4 ± 0.24 | 1.6 ± 0.01 | 69.7 ± 1.6 | 691.4 ± 25.8 | 12.7 ± 0.78 |

*Calcium, magnesium, and potassium ions were measured in milligrams, and manganese and chloride ions were measured in micrograms per gram of dry weight.


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higher than normal concentrations of atmospheric $CO_2$, there was an increase in the tuber weight and the tuber number per plant remained the same. With $CO_2$ enrichment of the root zone there was a significant increase in the tuber weight and a highly significant increase in the number of tubers per plant (Fig. 1 and Tables 2 and 3).

In a subsequent experiment, the root zones of potato plants were treated with $CO_2$ for 12 hours and the effects were evaluated at 2, 4, and 6 days. There was a progressive increase in the total plant dry weight from 2 to 6 days (Table 1) which is indicative of an increase in photosynthesis or a decrease in photorespiration. The concentrations of several organic acids were measured by gas chromatography (*7*) and confirmed by mass spectrometry. Both malic and citric acids increased in treated plants in proportion to the increase in total dry weight (Table 1), indicating an increase in carbon fixation by the $CO_2$-treated plants. Through the use of autoradiography we showed that label from $^{14}CO_2$ was translocated from the roots to the shoots. The bulk of the $^{14}C$ was found in malic acid. This work supports data from earlier studies (*8*) showing that when carbon is fixed by intact plant roots most of the label occurs in malate. By means of $^{14}CO_2$ incorporation studies, we found that approximately 18 percent of the dry matter increase came from $CO_2$ taken up through the roots (*9*).

Table 2. The effects of 12-hour $CO_2$ enrichment of root zones on tuberization in *Solanum tuberosum* L. 3 weeks after treatment. Control plants were treated with ambient air applied to both the roots and shoots; the enriched plants were treated with 45 percent $CO_2$ applied to the roots, and with ambient air applied to the shoots. Values are expressed as means ± standard error (dry weight basis).

| Treatment | Tuber weight (g) | Total number of tubers | Number of tubers per stolon | Stolon length (cm) | Root weight (g) | Shoot weight (g) |
|---|---|---|---|---|---|---|
| Control | 10.4 ± 3.8 | 7.0 ± 1.2 | 1.0 ± 0 | 2.0 ± 0.76 | 6.3 ± 1.6 | 32.8 ± 5.0 |
| $CO_2$ | 22.5 ± 6.0* | 51.0 ± 11.3* | 7.0 ± 0.68† | 25.0 ± 0.27† | 9.5 ± 2.8 | 56.6 ± 1.4* |

*Significant at the 95 percent confidence level. †Significant at the 99 percent confidence level.

Table 3. The effects of 12-hour $CO_2$ enrichment of root zones on tuberization in *Solanum tuberosum* L. 6 weeks after treatment. Control and enriched plants were treated as in Table 2. Values are expressed as means ± standard error (dry weight basis).

| Treatment | Tuber weight (g) | Total number of tubers | Number of tubers per stolon | Root weight (g) | Shoot weight (g) |
|---|---|---|---|---|---|
| Control | 77.4 ± 9.6 | 30.0 ± 13.0 | 1.0 ± 0 | 127.1 ± 23.0 | 412.3 ± 41.0 |
| $CO_2$ | 139.8 ± 10.0* | 152.0 ± 8.6† | 6.0 ± 1.2† | 113.2 ± 10.6 | 538.9 ± 22.4* |

*Significant at the 95 percent confidence level. †Significant at the 99 percent confidence level.

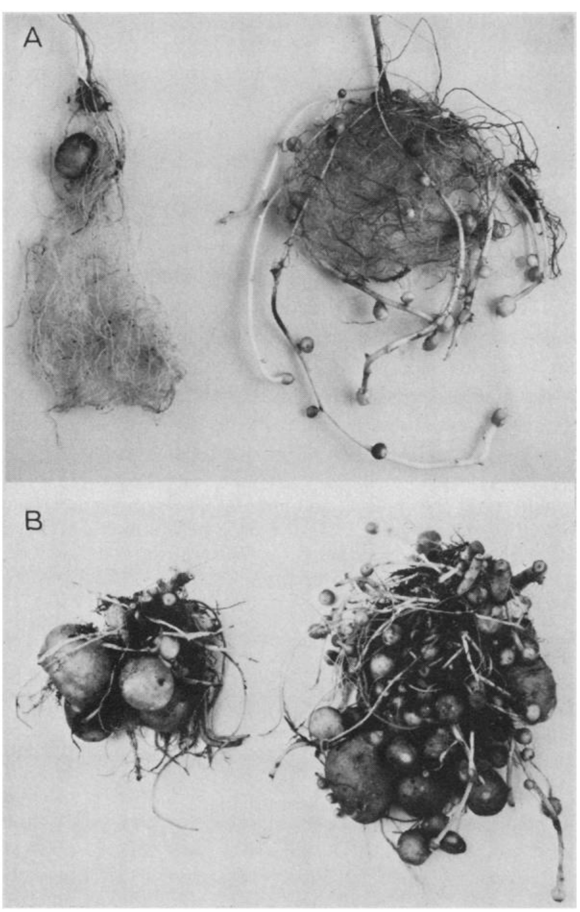


Fig. 1. The effects of 12-hour $CO_2$ enrichment of root zones on stolon elongation, tuber initiation, and growth in *Solanum tuberosum* L. (A) 3 weeks and (B) 6 weeks after treatment. Controls are at left and $CO_2$-treated plants at right.

Carbon dioxide treatment of root zones also selectively affected the uptake of minerals by the plants. This analysis was accomplished by neutron activation analysis and gamma-ray spectrometry with a high-resolution Ge(Li) detector and a programmable multichannel analyzer. Total plant $Ca^{2+}$ and $Mg^{2+}$ increased, whereas $Mn^{2+}$ and $Cl^-$ decreased; $K^+$ showed no change (Table 1). Chlorophyll levels as measured by acetone extraction (*10*) of treated plants increased in proportion to the increase in total dry weight. This increase lagged slightly behind the dry weight increase (Table 1).

Considering the worldwide economic and nutritional importance of potatoes, this research suggests the possibility of underground $CO_2$ enrichment as a means of increasing productivity, possibly by means of encapsulation of $CO_2$.

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