EFFECT OF SOIL AIR OXYGEN DEFICIENCY ON TOMATO YIELD

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ABSTRACT
Due to the environmental changes, especially global warming, water scarcity will be more serious in the water shortage areas. Efficient and judicious husbandry of the limited water resources is very important. Usually irrigation water is applied considering only the plant water need whereas the impact of the excess water on the soil air O₂ is ignored. Applied water fills the soil pores, replaces the soil air and reduces the amount of soil air O₂. Lack of or insufficient soil air O₂ reduce root growth, nutrients availability and photosynthesis rate, result in sever reduction in crop yield.

The study was conducted in a greenhouse at the Okinawa Subtropical Station, JIRCAS. Five wooden boxes (180cmX90cmX30cm) were connected with each other. Six galvanized batteries along with a T-type thermocouple, was set at the entrance of the first box and at the end of each box. Nine tomato (var. First Power) seedlings were transplanted in each box on February 18, 2005, and grown as a normal crop. At the flowering stage, soil surface in the boxes was covered by white polyethylene sheets and closed tightly to stop entry of air into the soil through the soil surface. Tomato was irrigated as and when required with a PVC pipe inserted in the surface of the boxes. We successfully developed a soil air O₂ creation technique connecting wooden boxes with each other and in situ soil air O₂ measurement using the galvanized battery. The results revealed that the amount of soil air O₂ gradually reduced from the first box to the last one. The available soil air O₂ concentration in the first box was 20.1% while it was 12.8 % in the last box. Due to the reduction in soil air O₂, chlorophyll content and root dry matter were drastically reduced causing reduction of tomato yield from 2 to 18%. The tomato yield was 28.5 ton/ha in the first box, while 23.4 ton/ha in the last box. The seasonal mean soil air O₂ indicated that by decreasing the available soil air O₂ content by 1%, the tomato yield would reduce by 0.88 t/ha. Therefore, consideration of the balance between soil air O₂ and soil water while deciding amount of irrigation water may increase crop yield, water savings and water use efficiency.

KEYWORDS: soil air O₂ deficiency, yield, root, soil air O₂ and yield relations, water saving.
INTRODUCTION
The need for one of the major plant nutrient- oxygen (O₂) – is often forgotten. The necessity of O₂ for the growth of plants has been known since 1668 [1]. Plant roots take up O₂ and give off CO₂. In the plant root zone, O₂ comes from the soil air that fills spaces between particles of soil, which ultimately exchanges with the air above the ground. A soil must breathe and refresh its O₂ supply or plant roots will not flourish [2] and suffocate in soggy soil because water displaces air. Plants can survive for about one month after a lot of rainfall by extracting water held in the soil, but plants exhaust soil O₂ within a few days if soil O₂ is not replenished by gas exchange between the soil and the ambient air [3]. Higher O₂ concentrations in the soil atmosphere are necessary to maintain normal root growth at higher temperatures to the decreasing solubility of O₂ in the soil solution as the temperature increases. Root growth stopped in 30 plant species studied when O₂ was entirely removed from the soil, most of the species maintained a slow growth rate in 0.5 % O₂ for a limited period of time, and rate of supply rather than the concentration influences the rate of growth [4].

Every plant has a different capacity for dealing with soil air O₂ deficiency, because agricultural crops vary widely in the O₂ requirement of their roots. Tomato (Lycopersicon esculentum) is a popular and important vegetable grown throughout the world with intermittent irrigation. For example, tomatoes need large quantities of O₂ for maximum growth, while soybean can tolerate low O₂, sugar beets and most root crops require relatively high O₂ while O₂ requirement of small grains are intermediate [5]. An oxygen diffusion rates (ODR) of 30 to 40 X10⁻⁸g.cm⁻²min⁻¹ at 8-inch depth as critical for tomato plants was suggested [6]. Tomato plants established in containers of soil with different ODR that influenced the susceptibility of plants to airborne oxidants, reduced plant vigor and could affect the susceptibility of plants to airborne oxidant damage under field conditions at the lower O₂ treatments [7]. The roots of cabbage and maize under surface distributed wider than that under subsurface at 0 to 20 cm depth with a low density, while under the subsurface distributed wider than surface at 30 to 40 cm depth with low density which may be due to the variation of soil O₂ under two irrigation methods [8]. However, most of the irrigation plans do not consider the impact of excess water application on soil air O₂ which is related to root growth. Application of excess irrigation water reduces the amount of soil air O₂ as well as enhances leaching of nutrients to deeper soil layers, thus hampering root growth and pollutes the ground water. If water is applied judiciously taking into consideration of soil air O₂, it will promote root growth which will require less amount of irrigation water and could avoid ground water pollution from the applied fertilizers. As an alternative way of water saving, it is important to conduct research turning the attention to soil-air-oxygen dynamics for the improvement of water use efficiency and reduction of ground water pollution. Therefore, we have conducted the experiment with the objectives a) to investigate the effect of soil air O₂ deficiency on the yield of tomato, and b) to study the relationship between the soil air O₂ deficiency with root growth and tomato fruit yield.

MATERIALS AND METHODS
The study was conducted at the Okinawa Subtropical Station (24°23′N, 124°12′E) of the Japan International Research Center for Agricultural Sciences (JIRCAS), Ishigaki, Japan. To study the effect of soil air O₂ deficits on plant growth and development, it is necessary to create soil air O₂ deficiency at the plant root zone. It’s a difficult task, because the atmosphere contains O₂ and the atmospheric O₂ easily mix with the soil air O₂. Preparing five control boxes and connecting with each other by the PVC pipe, and thus the soil O₂ deficiency at the plant root zone was successfully created [9]. To conduct the study, five air tight wooden boxes measuring 180cm X 90cm X30cm (length X breadth X depth) were purposively prepared. All joints of the boxes were sealed to stop entry of air. The bottom of each box up to 8 cm was filled with gravels and covered by white polyethylene sheets. Small holes were made on the polyethylene sheets to ensure air circulation. Each box was filled with 385 kg air dry soil. Two perforated PVC pipes were inserted at the bottom of each box as air inlet and another perforated PVC pipe was placed on the soil surface to use as an air outlet. The boxes were connected with each other with PVC pipe. Boxes were kept inside the greenhouse of the newly constructed indoor lysimeter [10]. After calibration, six O₂ sensors were used to measure soil O₂ in this experiment. Along with a T-type thermocouple, sensors were fixed inside the PVC pipe at six points-
at the entrance of the first box and at the end of each of the five boxes. To prevent the external temperature effect, each box was covered with an aluminum foil and painted with white paint. T-type thermocouple was set in the middle of each box at 10 cm depth to measure soil temperature and data were recorded every 30 minutes by CR10X data logger. Details of the experimental box preparation and measurement procedures were also described [9].

Nine tomato (Var. First power) seedlings were transplanted at 20 cm distance in the middle of each box on February 18, 2005.

In each box, one tensiometer was installed, every morning tensiometers were read, and when the tension exceeded pF 2.4 applied irrigation water. The crop was grown as a normal crop up to flowering. Experimental tomato at different stages is shown in Figure 1. At the beginning of flowering stage, on April 4, 2005, upper side of the boxes was covered and sealed by white polyethylene sheet so that air can not enter through the soil surface and also to prevent soil temperature increase. Adjacent to the tomato seedlings, white polyethylene sheets were carefully attached by gum and thus entry of air was completely stopped through the surface. To enhance the flowering and fruiting of tomato, tomato tone hormone was applied equally in each plant once in a week. Following the application of the treatments (on April 4 2005), leaf chlorophyll content was measured three times on April 19 & 25, 2005 and on May 3, 2005. Up to the five clustering, tomato fruits were allowed to bear and after the fifth clustering, the top of the plant was cut. Matured tomato was harvested twice in a week until end of the season. Harvesting of tomato started on April 27, 2005 and the final harvest was done on June 9, 2005. Soil of each box was sieved by a 2 mm mesh to collect roots, cleaned by tap water, dried in an electric oven at 70 °C for 10 days and recorded the root dry matter weight.

RESULTS AND DISCUSSION

Soil and air temperature
The soil temperature in the middle of each box was measured and shown in Figure 2. Soil temperature did not vary greatly among the boxes. The white polyethylene sheets helped in maintaining identical temperature in the boxes. Soil temperature was always greater than air temperature. Soil temperature followed the trend of air temperature. Therefore, the variations in soil temperature did not exert effect on the soil air O₂ concentration.

Soil air O₂
Under ambient condition at the entrance of box 1 (S1), the air O₂ concentration was 21% (Figure 3) which indicates that the galvanized battery measured the soil air O₂ properly. Compare to the S1, soil air O₂ reduced gradually up to the last box, resulting that those boxes had the soil air O₂ deficiency. Compare to the S1, daily soil air O₂ reduced up to 12 % that is 40 % less in the other boxes (Figure 3). The mean seasonal soil air O₂ from 94 to 162 days showed that O₂ reduced gradually in the boxes towards the box 5. The O₂ concentration was reduced by 10, 13, 15, 18 and 36 % at the end of the boxes 1, 2, 3, 4 and 5, respectively (Figure 4).
Figure 2. Daily Variation of soil temperature and air temperature in the experimental boxes

Figure 3. Daily variation of soil air oxygen and oxygen deficiency in tomato
Daily and seasonal mean results of soil air O\textsubscript{2} shows that there was soil air O\textsubscript{2} deficiency and the plant roots suffered from the soil air O\textsubscript{2} deficiency. Such soil air O\textsubscript{2} deficiency effect was exerted on the tomato yield and dry matter production. Air entered through the first box and out at the end of the fifth box, so there was a continuous flow of air from the starting to the end of the boxes. The differences of the soil air O\textsubscript{2} content between the entrance of box 1 and end of the box 5 is distinct which is not much distinct in the middle boxes. Impeded exchanges of gases between the soil and the atmosphere resulted to the soil air O\textsubscript{2} deficient condition by reducing the soil air O\textsubscript{2}.

**Chlorophyll content**

Chlorophyll content of the leaves was affected by the soil air O\textsubscript{2} deficiency. The results showed that the relative leaf chlorophyll content reduced gradually with soil air O\textsubscript{2} (Figure 5). Plants in lower O\textsubscript{2} level develop strong typical iron chlorosis resulting reduction of iron concentration and manganese but the plants look normal [11].

**Root dry matter**

Tomato roots showed a drastically decreasing trend in the soil air O\textsubscript{2} deficient boxes (Figure 6). Root dry matter reduced from 20 to 61 % in boxes
2 to 5, indicating that the tomato roots were very sensitive to the soil air O$_2$ deficiency. Compare to the box 1, root dry matter yield reduced by 20, 50, 51 and 60 % in the boxes 2, 3, 4 and 5 respectively. However, the root dry matter sharply reduced up to box 3, then the reduction in box 4 and 5 was smaller than boxes 2 and 3.

Tomato root dry matter weight

<table>
<thead>
<tr>
<th>Box Numbers</th>
<th>Root dry matter (g/box)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Box 1</td>
<td>34.62</td>
</tr>
<tr>
<td>Box 2</td>
<td>27.69</td>
</tr>
<tr>
<td>Box 3</td>
<td>17.26</td>
</tr>
<tr>
<td>Box 4</td>
<td>17.12</td>
</tr>
<tr>
<td>Box 5</td>
<td>13.55</td>
</tr>
</tbody>
</table>

Figure 6. Root dry matter yield and reduction of tomato root as affected by soil air oxygen deficiency

Tomato yield

The tomato yield reduced from 2 to 18 % in the soil air O$_2$ deficient boxes as compared to box 1 (Figure 7). It reveals that, soil air O$_2$ deficiency up to 17.5 % reduces least amount of tomato yield (2 % less) but further soil air O$_2$ deficiency cause drastically reduction of tomato yield. Compare to the box 1, tomato yield reduced by 2, 10, 13 and 18 % in the boxes 2, 3, 4 and 5 respectively.

Relations between yield and soil air O$_2$

Root dry matter yield decreased with soil air O$_2$ reduction (Figure 8). The reduction followed two distinct phases, a sharp reduction of about 50% roots with 4% reduction in O$_2$ and a gradual reduction in root dry matter afterwards. This result suggested that the roots were very sensitive to slight changes in soil air O$_2$.

Tomato yield reduced with the soil air O$_2$ deficiency and the data fitted with the regression equation shows that reduction of 1 % soil air O$_2$ reduces tomato yield by 0.88 t/ha (Figure 9). However, in this experiment the size of the each experimental box was 0.162 m$^2$ with 9 tomato plants grown in one box. This represented relatively lower plant population than under field condition. Therefore, due to the soil air O$_2$ deficiency the reduction of tomato yield would have been increased manifold if a plant population to that of a field had been maintained. In this study, connecting five boxes with each other and covering the soil surface with white polyethylene sheet gas exchange through the soil surface was completely stopped. This created soil air O$_2$ deficient condition in the experimental boxes (Figure 3 & 4). Soil air O$_2$ stress quickly damages plants and eventually reduces yield of most crops [12]. Plant water use, nutrient uptake, photosynthesis, etc. decreases when soil air O$_2$ is either reduced or excluded from the plant root zone hampering root respiration.
Therefore, root dry matter was reduced drastically at the soil air O$_2$ deficient boxes (Figure 6). Under soil air O$_2$ deficient condition, metabolic ion absorption is depressed, iron and manganese deficiency occur resulting chlorosis in plants [11]. This drastically reduced photosynthetic efficiency of plants. All these factors resulted in reduction of tomato fruit yield (Figure 7). From the results, it appears that a balance between water application and soil air O$_2$ availability is important to maintain optimum soil air O$_2$ level for increased tomato yield. The reduction of soil air O$_2$ up to 17.5 % reduced yield slightly (2 %) but further reduction of soil O$_2$ drastically reduced tomato yield (Figure 9). Results indicated that sacrificing 2 % tomato yield and to maintain 17.5 % soil air O$_2$ at the plant root zone, a large amount of irrigation water could be saved and that saved water could be use to extend irrigation facilities to more areas. However, the amount of irrigation water necessary to maintain 17.5 % level of soil air O$_2$ need to be determined.

CONCLUSION

Soil air O$_2$ deficiency reduced the relative chlorophyll content and root dry matter was drastically reduced, consequentially the tomato yield decreased (Figure 7). This suggests that maintaining soil air O$_2$ level above 17.5 % is essential for optimum tomato yield.

\[
y = -1.8961x + 22.347
\]

\[R^2 = 0.5368\]
yield was reduced (2 to 18%). Reduction of soil air $O_2$ up to 17.5 % reduced tomato yield by 2% but further reduction of soil air $O_2$ drastically reduced tomato yield. The seasonal mean soil air $O_2$ indicated that by decreasing the available soil air $O_2$ content by 1%, tomato yield would reduce by 0.88 t/ha. Consideration of a balance between soil air $O_2$ and soil water during deciding amount of irrigation water may increase tomato yield, water savings and water use efficiency. Sacrificing 2 % tomato yield and to maintain 17.5 % soil air $O_2$ at the plant root zone, a large amount of irrigation water could be saved and that saved water could be use to extend irrigation facilities to more areas.

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