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Root morphology of greenhouse produced muskmelon under sub-surface drip irrigation with supplemental soil aeration

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ABSTRACT

A fractional factorial experiment was designed to study the response of greenhouse-produced muskmelon root system to 3 levels of sub-surface drip irrigation in combination with drip-tubing placed at 3 different depths in the soil, and 4 frequency levels of supplemental soil aeration. Drip irrigation (I) levels were 70, 80, and 90% of field capacity (I_{70}, I_{80}, I_{90}) in combination with sub-surface tubing placement depth (D) at 10, 25, and 40 cm (D_{10}, D_{25}, D_{40}). Supplemental aeration frequency levels were none, daily, and at 2 and 4-day intervals (A_N, A_1, A_2, A_4). Total root length, surface area, and root volume and their distribution by diameter of the root system were measured using the WinRHIZO image analysis software. The results showed that the total length and surface area for D_{40} increased by about 48% and 24%, respectively than D_{10}. The two root parameters for A_1 increased by 83% and 63%, respectively than A_N. For the I_{70} treatment, the two parameters increased by 10% and 20%, respectively than I_{90}. These effects were primarily due to changes in these morphological parameters for the $\leq$1 mm diameter roots.

1. Introduction

The abiotic (i.e., soil physical/chemical and atmospheric factors) and biotic (i.e., animals, insects, diseases, weeds) production environment for muskmelon in the semi-arid climate of the lower reaches of the Yellow river in China is never ideal. In this context, drip irrigation and protective structures are also being used increasingly in China to improve water use efficiency, reduce insect damage, maintain more uniform atmospheric conditions, and improve market quality of the produce for the fresh food market (Jiang et al., 2003). For muskmelon, the protective structures are usually small (0.1–0.2 ha), low-cost frames with removal plastic covers that are constructed over natural soil in the fields. Sub-surface drip irrigation in conjunction with these structures significantly improves water use efficiency compared to traditional spray or furrow systems (Chang et al., 2013). The reason is that sub-surface drip irrigation permits producers to more precisely tailor irrigation amount and frequency to the plant consumptive use. This minimizes water losses from percolation below the root zone, surface runoff, and bare soil evaporation. On the other hand, the smaller irrigation amounts through equally spaced emitters or tiny holes in the drip irrigation tubing wet only a portion the root-zone soil volume. The wetted soil volume depends on the irrigation application rate and amount and the soil hydro-physical characteristics. Consequently, permanent drip irrigation installations have to be properly designed and operated to supply water and wet a soil volume that is optimal for the given crop or crop sequence (Mostaghami et al., 1981; Schwartzman and Zur, 1986; Michelakis et al., 1993; Zur, 1996; Al-Qinna and Abu-Awwad, 2001; Assouline, 2002; Acar et al., 2009). Nevertheless, producers operationally adapt commercially available drip irrigation equipment to given crop and environmental conditions. In this context, producers can vary the sub-surface depth of the buried drip tubing and the rate, amount, and frequency of irrigation. Under protected cultivation, these practices would need to be optimized so that the roots can access the water in wetted portion of the root zone. It is assumed that the roots will populate and proliferate in the wetted volume due to hydro-tropism. Hydro-tropic root response to soil water potential gradient is not well understood (Chamovitz, 2012; Cassab et al., 2013; Wyatt and Kiss, 2013)

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In addition to soil water, it is well-known that mesophytic plant roots require an adequate and continuous supply of soil O_2 in order to respire, grow, develop, and function normally. This supply is obtained primarily from the soil air in contact with the root system. However, if the roots are confined to the soil volume wetted under sub-surface drip irrigation, the possibility of hypoxia in the wetted portion of the root zone under sub-surface drip irrigation is almost certain, especially in heavy soils with slow internal drainage and during the period immediately after irrigation.

Rhizosphere hypoxia (induced by flooding, soil compaction, poor drainage, excessive irrigation etc.) negatively influence crop yield, shoot and root growth, and quality of produce (Blokhina et al., 2003; Oliveira et al., 2013). Hypoxia causes stomatal closure, reduction in transpiration rate and photosynthesis, and leaf chlorophyll and protein content (Bai et al., 2013; Oliveira et al., 2013). Gao et al. (2011) showed that hypoxia significantly increased activity of nitrate reductase and glutamate synthase, along with levels of nitrate, ammonium, amino acids, heat-stable proteins, polyamines and H_2O_2 in the soil.

In addition to water savings under protective cover, sub-surface drip irrigation allows for application of nutrients and other dissolved agri-chemicals directly to the wetted portion of root zone. Supplemental soil aeration is also possible either along with the water (termed as aerated irrigation or airgation) or separately, and can effectively improve the oxygen level in rhizosphere. Studies have shown that aerated irrigation can significantly improve crop yield and quality (Bhattarai et al., 2005; Pendergast et al., 2013), especially on heavy clay and saline soils (Bhattarai et al., 2004, 2006, 2008; Zhu et al., 2012). Air injected via subsurface drip irrigation tubes positively affected growth of corn compared to the control without air injection. Leaf area per plant was 1.48 times greater, grain filling, root distribution, stem diameter, plant height, and number of grains per plant were much higher (Abuarab et al., 2013). Niu et al. (2012) showed that soil aeration improved the soil enzyme activity and promoted the growth of plants. Similarly, Bhattarai et al. (2006) and Chen et al. (2011) found aeration significantly improved the dry matter accumulation, yield, and water use efficiency of cotton, wheat, tomato and pineapple in a heavy clay soil. Xu et al. (2013) reported that rice seedlings grown in oxygenated solutions had higher root dry matter, root length, root vitality, and root absorption area compared with the non-oxgenated control. The plants had higher soluble sugar content, root vigor, and the activities of glutamine synthetase (GS), glutamic acid oxaloacetate transaminase (GOT), and glutamic acid–pyruvic acid transaminase (GPT). Previous studies have shown that aerated irrigation could improve yield and quality of greenhouse muskmelon, and the aeration once every two days provided the maximum increases in these two factors (Xie et al., 2010). These studies strongly suggest that increased access to O_2 by supplemental aeration has positive impacts on plant growth and physiology. Since supplemental aeration increases air in the root zone, it is reasonable to infer that observed positive effects are indirectly linked to the response of the plant root system. It is well-known that, within limits imposed by their genetics, plant can modify their root system architecture, distribution, anatomical structure, and metabolic activity in order better adapt to soil conditions such as water, nutrient, and O_2 availability (Weaver and Bruner, 1927; Jovanovic et al., 2007; Osmont et al., 2007; Hodge et al., 2009; Ingram and Malamy, 2010). However, there are few reports on how aeration affects plant root morphology and activity. In the absence of such empirical findings, bio-physical models cannot be developed that describe plant root response to supplemental soil aeration and their underlying mechanisms.

Based on the foregoing examination of the literature, this controlled study focused on measuring several parameters of the root system morphology of greenhouse produced muskmelons under sub-surface drip irrigation and supplemental soil aeration. No previous reports were available on such investigations. It was hypothesized that varying the irrigation rate and amount along with the depth of the drip irrigation tubing would result in differing wetted volumes in the root zone. Information on how the muskmelon plant roots adapt morphologically to the partial wetting of the root zone and to supplemental soil aeration would provide guidance for field production practices as well as indications of possible mechanisms for the observed responses.

2. Materials and methods

The experiment was implemented from April to July 2014 in a 108 m long and 8 m wide greenhouse located E108°02′, N34°17′, at Yangling, Shaanxi Province, China. The climate of Yangling is semi-arid with an average of 210 frost-free days. Soil properties were: dry bulk density 1.35 g cm^{-3}; porosity 49.4%; field capacity 28.2% by weight = 38% by volume; pH 7.82. The texture was a clay loam (sand 25.4%; silt 44.1%; and clay 30.5%).

Muskmelon cultivar Shantian No. 1 was sown in commercial seedling plugs (Northwest New Horizon Facilities Agriculture Development Co. Ltd., Yangling Shaanxi, China), and transplanted after 20 days in 2 rows spaced 0.5 m apart on both sides of 0.2 m high ridges that were separated by 0.15 m deep furrows. Seedlings were spaced 0.40 m apart within the rows. All agronomic management measures taken during growth period of muskmelon such as fertilization, agricultural chemicals spraying, etc. were consistent with local production practice.

The aim of the experiment was to examine muskmelon root growth under 3 levels of sub-surface drip irrigation in combination with drip-tubing placed at each of 3 depths in the soil, and 4 levels of supplemental soil aeration. Experimental plots were of 5.5 m long with 2 rows of 13 plants for each row and 1 m separation between plots. Before transplanting, 2 parallel drip irrigation tubes were buried 0.50 m apart to the appropriate depth. The tubing was 16 mm diameter, with emitter spacing of 0.30 m. Each plot had 35–36 emitters, each with a discharge rate of 1.5 L h^{-1} under the operating conditions for the drip irrigation system.

A full 32×4^1 factorial of the 36 experimental treatment combinations and would require 108 plots for 3 replicates. Since there was not enough space to accommodate all these plots, a balanced one-third fractional factorial design (Wu and Hamada, 2000; Collins et al., 2009) was developed using 12 of the 36 treatment combinations. The transposed design matrix for the 12 treatment combinations was:

Combination	1	2	3	4	5	6	7	8	9	10	11	12
Depth (D)	D_{10}	D_{10}	D_{10}	D_{10}	D_{25}	D_{25}	D_{25}	D_{25}	D_{40}	D_{40}	D_{40}	D_{40}
Aeration (A)	A_N	A_1	A_2	A_4	A_N	A_1	A_2	A_4	A_N	A_1	A_2	A_4
Irrigation (I)	I_{70}	I_{80}	I_{90}	I_{70}	I_{80}	I_{90}	I_{70}	I_{80}	I_{90}	I_{70}	I_{80}	I_{90}

With 3 replicates this design reduced the required number plots from 108 to 36. The design is balanced since each level occurs the same number of times within each factor (row). However, every pair of levels occurs the same number of times for factor pairs (A D) and (A I) but not for pair (D I). For the factor pair (D I), there are 9 level pairs but pairs (D_{10} I_{70}), (D_{25} I_{80}), and (D_{40} I_{90}) occurs twice while the remaining 6 level pairs occur once. While not fully orthogonal, the design was statistically efficient as possible.

The gravimetric water content (θ_g) at the time of transplanting was measured and all the plots were surface irrigated with 385 L (equivalent to 70 mm depth) applied to each plot. The irrigation levels designated as I_{70}, I_{80}, and I_{90} were based on wetting the soil volume (V_s) in 0.60 m of the soil profile (V_s = 5.5 m^2 × 0.6 m) to 70, 80, and 90% of the gravimetric field capacity. Two irrigations were applied to the appropriate experimental plots via sub-surface drip irrigation (16 mm diameter tubing with emitter spacing of 30 cm) at 23 and 60 days after transplanting. These applications were based