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Effects of uneven vertical distribution of soil salinity under a buried straw layer on the growth, fruit yield, and fruit quality of tomato plants

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ABSTRACT

Soil salinity is often heterogeneous, but plant response to uneven salt distributions in the vertical direction (USDVD) of the root-zone under buried straw layer is seldom studied in tomato (*Solanum lycopersicum* L.var. Yazhoufenwang). Our objective in this study was to evaluate the effects of USDVD under a buried straw layer on changes in water consumption, root distribution, yield, fruit quality, K^+, Na^+, Ca^{2+} concentrations of leaves and fruits as well as stable carbon isotopic compositions ($\delta^{13}C$) of leaves for tomato plants grown in the greenhouse. To achieve this objective, pot experiments were conducted from April to July in 2014 and 2015. The treatments, $T_{1:1}$, $T_{1:5}$, $T_{2:4}$ and $T_{3:3}$, were established by setting the upper soil layer with $EC_{1:5}$ (the electrical conductivity of a 1:5 dry soil: water mixture) 0.38 ms cm^{-1}, 0.38 ms cm^{-1}, 0.76 ms cm^{-1} and 1.14 ms cm^{-1}, respectively, and the lower soil layer with $EC_{1:5}$ 0.38 ms cm^{-1}, 1.90 ms cm^{-1}, 1.52 ms cm^{-1}, and 1.14 ms cm^{-1}, respectively. In addition, a capillary barrier, made of straw, at a depth of 17 cm and with a thickness of 3 cm, was set between the upper and lower soil profile. The roots could penetrate through the straw layer, even though the soil salinity in the lower soil layer was relatively high ($T_{1:5}$). Compared to equal salinity distribution treatments ($T_{1:1}$ and $T_{3:3}$), there was a significant compensatory water uptake and root growth from the low salinity soil profile under USDVD treatments ($T_{1:5}$ and $T_{2:4}$). In 2014, the water consumption and root density in the upper soil layer under USDVD treatments ($T_{1:5}$ and $T_{2:4}$) were 1.20 times and 1.38 times those of the equal salinity distribution treatments ($T_{1:1}$ and $T_{3:3}$), respectively. The Na^+ concentrations of leaves for $T_{1:5}$ and $T_{2:4}$ were 15.1% and 48.9% of $T_{3:3}$, respectively, whereas the K^+ concentrations of leaves for $T_{1:5}$ and $T_{2:4}$ were 2.1 times and 1.4 times that of $T_{3:3}$, respectively, resulting in significantly higher K^+/Na^+ ratios for $T_{1:5}$ (10.17) and $T_{2:4}$ (2.06) than $T_{3:3}$ (0.72); the $\delta^{13}C$ value of $T_{3:3}$ (−28.46) was significantly higher than that of $T_{1:5}$ (−29.17), whereas there was no significant difference for $\delta^{13}C$ between $T_{1:5}$ and $T_{1:1}$ (−29.12). Across the two years, the average yields of $T_{1:5}$, $T_{2:4}$ and $T_{3:3}$ were 20.3%, 47.1%, and 64.9% lower than that of $T_{1:1}$, respectively, whereas the soluble sugar contents of the fruits in $T_{1:5}$, $T_{2:4}$ and $T_{3:3}$ were 21.3%, 76.5% and 97.6% higher than that of $T_{1:1}$. The overall results suggest that the USDVD treatments under a buried straw layer could relieve the salt stress and benefit the quality and quantity of tomato plants grown in saline soil.

1. Introduction

Due to the sustained growth of land-use for industrial, environmental, and other purposes, as well as the increasing food demand caused by population growth, the shortage of land resources has become an urgent problem in China (Lin and Ho, 2003). The area of tideland resources is approximately 3,540,000 ha in China, and is considered one of the most important agricultural land reserves, especially in eastern China (Ren, 1996). The scientific and reasonable exploitation of land resources in coastal saline soil is critically important for relieve the population pressure and satisfy food demand in eastern China (Wang et al., 2013).

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Tomato (*Solanum lycopersicum* L.), one of the most improtant vegetable crops, is moderately tolerant to salinity, and is commonly cultivated in saline areas (Lu et al., 2010; Amjad et al., 2014). However, the high salt concentrations in reclaimed coastal area seriously disrupted tomato crop growth at all stages of growth, and significantly reduced crop yield. To alleviate the effects of salt stress on plants, leaching was employed by flooding or drip irrigation to reduce the salt content of the surface soil with fresh water or brackish water (Fu et al., 2014; Chen et al., 2015). However, salt could move upward and accumulate on the soil surface by capillarity from the subsoil and shallow ground water in response to evaporation gradients during growth in the coastal area (Dong et al., 2010). As a result, the lower salt concentration on the surface soil by leaching could only be maintained for a relatively short duration. To solve this problem, buried layers, made of straw, gravel, or artificial materials, were used as the capillary barrier to prevent salt accumulation on the soil surface, and consequently alleviate salt stress in crops (Rooney et al., 1998; Zhang et al., 2012; Sun et al., 2014; Ityel et al., 2014). Because straw was easy to get from the surrounding area at a low price, the straw layer was usually used as the capillary barrier in the coastal saline land. In addition, other benefits of straw layer burial, such as decreased soil pH, increased leaching efficiency, decreased particle density, and improved soil quality and harvest earliness, have also been reported by other researchers (Fan et al., 2012; Zhao et al., 2002).

Due to the improvement of the salt leaching efficiency during the water infiltration process and the reduction of salt accumulation in the top soil layer by capillary break effects, recent studies have indicated that the straw layer treatment could result in the spatially heterogeneous distribution of salt in the soil profile (Zhao et al., 2014, 2016), with the upper soil layer above the buried layer having a considerably lower salt concentration than that of the lower soil layer (Qiao et al., 2006; Zhang et al., 2010). In addition, a recent study indicated that roots of plants could easily penetrate through barrier layers with minimal disturbance if the layer has been designed properly (Dara et al., 2015). Once the layer was buried at a relatively shallower depth and crop roots could easily penetrate through them, the distinct salt concentrations for the upper and lower soil layers (Qiao et al., 2006; Zhang et al., 2010) could result in the vertical heterogeneous distribution of salinity in the root-zone. Furthermore, uneven salt distributions in the root-zone could benefit the growth and improve the quality and quantity of crops (Sonneveld and de Kreij, 1999; Malash et al., 2005; Incerti et al., 2007; Dong et al., 2010; Bazihizina et al., 2009, 2012). Previous researchers attributed the positive effects of non-uniform salt distributions in the root-zone to the increased root growth and water uptake in the low-salinity root portion, decreased Na^+ accumulation, and increased K^+ concentration and K^+/Na^+ ratio in leaves (Bazihizina et al., 2009; Tabatabaie et al., 2003; Flores et al., 2002; Kong et al., 2012). Whereas, the focuses of the above mentioned studies was on the responses of crops to the horizontal uneven salinity distribution, few researchers have studied the responses of plants to vertically uneven salt distribution in the root-zone (Bingham and Garbe 1970; Bazihizina et al., 2012). Eventhough a number of studies have investigated the effects of straw layer burial on salt and soil moisture dynamics and crop growth in saline soil (Chen et al., 2015; Zhao et al., 2014, 2016), few have addressed the effects of uneven salt distributions in the vertical direction (USDVD) with buried capillary barrier on crop growth, ionic concentration in leaves and fruits as well as stable carbon isotopic compositions ($\delta^{13}C$) of leaves. Previous studies demonstrated that most of the root system of tomato was concentrated in the top 40 cm of the soil profile (Machado and Oliveira, 2003). To make sure that tomato roots could easily penetrate through buried capillary barrier, in this study, we deliberately set straw layers at a relatively shallower depth (17 cm in depth). Furthermore, to simulate the vertical heterogeneous distribution of salinity in the field after salt leaching, we filled the upper and lower soil profile with different salinity soil. In this study, tomato plants were grown under four treatments from third-leaf to fruit maturity stages, and the effects of USDVD on tomato growth, fruit yield, fruit quality and root distribution were investigated. Additionally, to further understanding the mechanism of advantages of uneven vertical distribution of soil salinity, Na^+ concentration, K^+ concentration, K^+/Na^+ in tomato leaves and fruits as well as $\delta^{13}C$ in leaves were also studied.

The objectives were to determine (1) how tomato roots growth responds to the vertical heterogeneous distribution of salinity in the root zone and whether roots could penetrate through straw layer when the soil salinity in the lower soil layer was relatively high; (2) whether there were compensatory effects for water uptake and root growth in the low-salinity soil profile under USDVD treatments; (3) the effects of USDVD under a buried straw layer on the yield and quality of tomato; (4) the effects of vertical heterogeneous distribution of salinity on Na^+ concentration, K^+ concentration, K^+/Na^+ in tomato leaves and fruits as well as $\delta^{13}C$ in leaves.

2. Materials and methods

2.1. Experimental setup

The experiment was conducted from April-July 2014 and repeated in April-July 2015 in a greenhouse under nature light conditions without temperature control located at the Key Laboratory of Efficient Irrigation-Drainage and Agricultural Soil-Water Environment in Southern China, Nanjing, Jiangsu Province, China. The soil was taken from the coastal area of Dongtai, Jiangsu Province, and classified as silty sand with an $EC_{1:5}$ of 2.2 ms cm^{-1}. The concentrations of Ca^{2+}, Mg^{2+}, Na^+, K^+, $CO_3{}^{2-}$, $HCO_3{}^-$, Cl^- and $SO_4{}^{2-}$ in the saline soil with the $EC_{1:5}$ value of 2.2 ms cm^{-1} are 2.58 mmol kg^{-1}, 0.82 mmol kg^{-1}, 70.02 mmol kg^{-1}, 0.21 mmol kg^{-1}, 2.32 mmol kg^{-1}, 9.21 mmol kg^{-1}, 84.31 mmol kg^{-1} and 3.58 mmol kg^{-1}, respectively.

The pots those were used were 20.0 l (30 cm and 25 cm for the upper and lower diameters, respectively, and 42 cm deep), with a 0.5-cm hole drilled in the bottom to allow for drainage. After salt leaching, saline soils with different $EC_{1:5}$ (soil $EC_{1:5}$ values were 0.38 ms cm^{-1}, 0.76 ms cm^{-1}, 1.14 ms cm^{-1}, 1.52 ms cm^{-1}, and 1.90 ms cm^{-1}) were obtained. Peat substrate (GB-Pindstrup Substrate No.1, pH 6.0) was mixed with the original soil at a rate of 32.5 g pot^{-1} to obtain the new mixed soil with a bulk density of 0.94 g cm^{-3}. In addition, 0.326 g of urea ($CO(NH_2)_2$), 2.5 g of organic fertilizer (4% N, 4% P, and 4% K), 0.13 g of potassium sulphate (K_2SO_4), and 0.38 g of potassium dihydrogen phosphate (KH_2PO_4) per pot were mixed with the soil to meet nutrient requirements during plant growth. The soil in the pot was divided horizontally by a straw capillary into upper and lower soil layers, and weighed 8.6 kg and 12.9 kg, respectively. The straw capillary was made of rice straw, and its weight and thickness were approximately 50 g and 3 cm, respectively. The water-holding capacity (θ_f) of the mixed soil was 37% (Vol.). For the salt distribution in the upper and lower layers, four treatments, i.e., $T_{1:1}$, $T_{1:5}$, $T_{2:4}$ and $T_{3:3}$, which represents the soil $EC_{1:5}$ of the upper soil layer/$EC_{1:5}$ of the lower soil layer at the initiation of treatment at 0.38 ms cm^{-1}/0.38 ms cm^{-1}, 0.38 ms cm^{-1}/1.90 ms cm^{-1}, 0.76 ms cm^{-1}/1.52 ms cm^{-1}, and 1.14 ms cm^{-1}/1.14 ms cm^{-1}, respectively, were used in this study (Fig. 1). The pots were spaced at 50 × 50 cm.

Tomato (*Solanum lycopersicon* L. var. Yazhoufenwang) seeds were sown on 5 March and 15 March for the 2014 and 2015 seasons, respectively. When the third true leaf of the seeding had expanded