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RESEARCH ARTICLE

The influence of soil drying- and tillage-induced penetration resistance on maize root growth in a clayey soil

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Abstract

Soil drying may induce a number of stresses on crops. This paper investigated maize (*Zea mays* L.) root growth as affected by drought and soil penetration resistance (PR), which was caused by soil drying and tillage in a clayey red soil. Compared with conventional tillage (C) and deep tillage (D), soil compaction (P) and no-till (N) significantly increased soil PR in the 0–15 cm layer. The PR increased dramatically as the soil drying increased, particularly in soil with a high bulk density. Increased soil PR reduced the maize root mass density distribution not only in the vertical profile (0–20 cm) but also in the horizontal layer at the same distance (0–5, 5–10, 10–15 cm) from the maize plant. With an increase in soil PR in pots, the maize root length, root surface area and root volume significantly decreased. Specifically, the maize root length declined exponentially from 309 to 64 cm per plant with an increase in soil PR from 491 to 3 370 kPa; the roots almost stopped elongating when the soil PR was larger than 2 200 kPa. It appeared that fine roots (<2.5 mm in diameter) thickened when the soil PR increased, resulting in a larger average root diameter. The average root diameter increased linearly with soil PR, regardless of soil irrigation or drought. The results suggest that differences in soil PR caused by soil drying is most likely responsible for inconsistent root responses to water stress in different soils.

Keywords: clayey soil, root diameter, root elongation, soil compaction, water stress

1. Introduction

When a soil loses water, a series of physical, chemical and biological processes are induced. Crop roots experience multiple stresses in addition to water shortage. One of these stresses is a major restriction related to the physical degradation of the soil, which is indicated by the soil strength or soil penetration resistance (PR). Soil desiccation leads to increased soil suction and soil strength (Whalley *et al*. 2005; Dexter *et al*. 2007), restricting or even halting root elongation (Passioura 2002). This may harm the ability of the roots to absorb water and nutrients form the soil. In agricultural soils, PR is a principal factor that limits root growth and crop yield (Kadžienė *et al*. 2011; Tracy *et al*. 2011). Under various field conditions, a reduction in the yield of wheat was more closely related to the increasing of soil PR than to soil water stress (Whalley *et al*. 2006, 2008; Whitmore *et al*. 2011). Recent studies show that, as an independent abiotic stress (Bengough *et al*. 2011), soil PR can be considered a primary physical constraint on crop growth (Whalley *et al*. 2008; Whitmore *et al*. 2011). In many drying soils, the

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effect of PR on plant growth is greater than the direct effect of water stress (White and Kirkegaard 2010). Therefore, it is essential to investigate how soil PR affects the soil-crop water relationships under drought conditions.

The effect of soil strength on crop performance was measured at different degrees of soil compactness or relative bulk density, an index proposed by Håkansson and Lipiec (2000). The crop yield responded to the degree of soil compactness as a parabolic function, with an optimal yield response at a medium level of soil compaction (Arvidsson and Håkansson 2014). The mechanism for a yield increase in lightly compacted soil is not clear, but it can probably be attributed to increased unsaturated hydraulic conductivity and improved root-soil contact (Veen *et al*. 1992). In contrast to soil compacting, soil drying neither increases unsaturated hydraulic conductivity nor improves root-soil contact, but it can increase soil PR. There are numerous studies that focus on water stress or PR stress on crops, but few researchers appear to have investigated the effects of multiple stresses on crop roots (Haro *et al*. 2008; Hodge 2009). The literature on the effects of drought on crop roots might actually describe the effects of water stress and soil PR. Because of differences in soil PR, the effect of drought on crops can lead to inconsistent results at the same level of water stress.

Seasonal drought limits crop growth in red soils in South China. In the dry season, the clayey red soil has a high moisture content in the deep layer, which is still available for crops, but flow to the root zone where crops can take up the moisture is difficult (Chen *et al*. 2010). Hence, drought is usually attributed to the low unsaturated hydraulic conductivity of the red soil. However, drought might also result from a high soil PR under dry conditions. The clayey red soil is naturally strong due to the presence of the clay horizon in the subsurface, and the soil PR increases rapidly during soil drying. The high soil PR considerably constrains root elongation and distribution in the deep layer and reduces the ability of the roots to absorb soil water. Indeed, a drying soil can become strong enough to affect root growth at a soil water matrix potential as high as –100 kPa (Mullins *et al*. 1992). Hence, we hypothesized that soil PR aggravates seasonal drought by inhibiting crop root growth in red soil areas. Therefore, it is particularly important that we have a good understanding of how soil drying and soil PR affect root growth.

The aim of this study was to investigate how tillage treatments and the soil moisture status affected soil strength and how maize root performance responded to changes in soil strength. We performed a field experiment to modify the soil strength with different tillage treatments. We also performed a pot experiment to compare changes in soil strength due to soil compaction and irrigation. The soil states achieved in both the field and pot studies were linked to maize root performance so that the root responses to soil strength under different tillage treatments and moisture levels could be elucidated.

2. Results

2.1. Root distribution

The soil penetration resistance (PR) and root mass distribution in the field soil profile were measured in the maize jointing stage. As shown in Fig. 1-A, the soil PR was significantly different between tillage treatments. At 0–15 cm, as expected, soil compaction (P) had the highest PR, followed by no-till (N), and conventional tillage (C) and deep tillage (D) were the lowest. However, at a depth of 17.5–27.5 cm, the results were different. Treatment C had the highest PR, while other treatments in the same order. Overall, from the soil surface downwards, the PR distribution across the soil profile showed a pattern of "low-high-low". The largest PR values were observed at a depth of 10–15 cm in treatments P and N, and at a depth of 20–25 cm in treatments C and D. This result indicates that treatments P and N not only increased the PR in topsoil but also shifted its peak position upward by 10 cm. All of the changes in PR and its distribution affect maize root growth in the soil profile.

A major portion of the maize root mass was distributed in the topsoil layer and was subject to soil PR changes due to tillage. As shown in Fig. 1-B, more than 90% of the root dry weight was gathered from a depth of 0–20 cm, beneath which the root mass decreased sharply. The four treatments showed the same pattern of root distribution in the soil profile. However, the soil PR significantly affected the root distribution, revealing a negative relationship between root mass density and soil PR. In other words, the root mass density in the soil profile was in the order of D>C>N>P, contrary to the order of the PR in soil profile (Fig. 1). At a depth of 0–10 cm soil, the root mass density in treatment P was obviously lower than those in the other three treatments. At a depth of 10–30 cm soil, treatments P and N had lower root mass density than treatments C and P. At a depth of 30–40 cm, the crop had a very low root mass density, and the differences between the treatments were too small to be considered. The results indicate that soil PR significantly decreased the root mass density.

The root mass density in the horizontal distribution was also modified by soil PR. Fig. 2 shows that the root mass density decreases with increasing distance from the stem in the 0–20 cm soil layer. The major portion of the root mass was concentrated at 0–5 cm from the plant. However, at the same distance from the plant, a higher soil PR decreased the root mass density. The results show that the root mass