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Tillage practices affect biomass and grain yield through regulating root growth, root-bleeding sap and nutrients uptake in summer maize

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ABSTRACT

No tillage (NT) of summer maize (*Zea mays* L.) is the dominant agricultural practice in the annual double-cropping system of winter wheat–summer maize in the North China Plain, and the long-term NT is often unfavorable for the growth of maize roots. The aim of this study was to evaluate the effect of 2-year-old rotary tillage (RT) and plowing tillage (PT) based at NT soil on root growth, spatial distribution, nutrients uptake and grain yield in Wuqiao of the North China Plain. PT and RT significantly increased root biomass across 0–40 cm soil profile in the whole growth stage. Lower bulk density under PT and RT was compared to under NT in the 0–20 cm soil profile, and penetration resistance under NT was significantly higher than under PT and RT in the 0–30 cm soil profile. Root length density (RLD) in the uppermost soil profile (0–10 cm) had no evident differences among tillage practices at silking stage, but RLD under PT and RT was significantly greater than under NT at maturity. Moreover, RLD and root surface density (RSD) were significantly higher under PT than under NT in the topmost layer, 10–50 cm soil profile, but there were no differences in RLD and RSD among tillage practices at the deeper soil profile below 60 cm. PT and RT markedly improved the root-bleeding sap rate in the whole growth stages in 2011 and most growth stages in 2012. In addition, NH_4^+ and NO_3^- delivery rate under PT were significantly higher than those under RT and NT in 2011 and 2012, and under RT were significantly higher than under NT in 2012. The delivery rate of P, K, Ca, Mg, Fe and Zn in bleeding sap under PT was significantly higher than those under NT at different growing stages across the two years. Our results suggested that short-term PT and RT could increase root biomass, improve root spatial and temporal distribution, and enhance nutrients uptake, which resulted in higher biomass and grain yield of summer maize in the North China Plain.

1. Introduction

Plant roots are a fundamental component of terrestrial ecosystems and function to maintain the supply of nutrients and water to the plant (Spedding et al., 2004). Moreover, the above-ground growth and biomass yield is greatly dependent on the root system (Jeschke et al., 1997), and root development and distribution in the soil profile determine the capacity for nutrient uptake and water extraction by crop plants (Fageria, 2004). Hammer et al. (2009) pointed out that changes of the root system contributed more to historical corn yield increases than those of shoot. In general, root growth is determined by both plant genetic characters and soil physical and chemical properties, and shows high plasticity under different environmental conditions (Hodge, 2006; Lynch, 2011).

The potential of plants to obtain water and mineral nutrients from the soil is primarily attributed to their capacity to develop extensive root systems. However, soil compaction, especially in subsoil layers, restricts deep root growth and thus limits plant access to subsoil water and nutrients. In practice, tillage has been extensively adopted for its multiple functions, including change of soil properties, such as bulk density, penetration resistance and aggregate stability. Huwe (2003) reports that tillage influences both biotic and abiotic processes, modifying structural properties such as cracks, aggregates and pore continuity, as well as affecting soil aeration, temperature and moisture levels. By greatly changing soil properties, tillage also influences root growth. Mosaddeghi et al. (2009) concludes that the most important impact of tillage on crop

Abbreviations: NT, no tillage; RT, rotary tillage; PT, plowing tillage; RLD, root length density; RSD, root surface area density; V_7, seven leaves with visible leaf collars; V_{12}, twelve leaves with visible leaf collars; DAS, days after silking.

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development is achieved by affecting root development and function. Therefore, the root system serves as a bridge between the impacts of agricultural practices on soil and changes in shoot function and harvested yield.

It is generally accepted that roots are more likely to concentrate in the topsoil due to the greater availability of water and nutrients (Hodge, 2006; Lynch, 2011). As with impact of tillage on root distribution, no-tillage practice can gradually increase mechanical impedance of the surface soil, limiting the distribution of roots in the upper soil profile and root downward progression (Mosaddeghi et al., 2009). The roots are also thicker with less absorbing surfaces in rotary-tilled soil than plow-tilled soil, and finer and longer under tilled soil compared with no-tilled soil, generally more abundant under plow tillage than no tillage at all depths (Barber, 1971; Karunatilake et al., 2000). However, controversial result is found that no-tillage promotes greater and deeper water accumulation in the soil profile and greater root growth (Lampurlanés et al., 2001). Merrill et al. (1996) observes that spring wheat roots penetrate to greater soil depths under no tillage than conventional tillage, with larger root length density due to the cooler soil and superior soil water conservation in the near-surface zone.

Tillage practices affect soil properties, crop growth and nutrient uptake under various agro-ecological conditions. The uptake of water and nutrients are largely dependent on the root systems of crops (Spedding et al., 2004). The soil cultivation affects the rooting conditions of crops grown and also has direct impact on the root growth and nutrient uptake (Lipiec and Stepniewski, 1995). The root length density (RLD) is an important parameter for the evaluation of tillage system impact on crop growth and yield (Amato and Ritchie, 2002). Otherwise, the root system is one of the important components of plants, and has some important physiological functions, such as nutrient and water absorption, amino acid, and hormone (Noguchi et al., 2005). These matters partially participate in the root matter synthesis and physiological activities and substance transport with xylem sap taking effect on the shoot. Root development could influence plant water and nutrient use efficiency, which determine environmental impacts of agriculture (Fageria, 2004; Doussan et al., 2006). Bleeding sap is a manifestation of the root pressure. The quantity and components reveal the plant growing potential and root activity. Bleeding sap intensity varies with season, plant and soil conditions, and is consistent with root activity (Bialczyk and Lechowski, 1995; Peuke, 2000). Given the difficulty of evaluating root systems in field trials, root-bleeding sap is helpful to learn root behavior, especially nutrient uptake (Amos and Walters, 2006).

The North China Plain supplies more than 50% of the wheat and 33% of the maize produced in China (Yang and Zehnder, 2001). Double cropping winter wheat and summer maize is the predominant model in this region. In practice, rotary-tillage is performed before sowing winter wheat, and summer maize is sowed under NT conditions right after harvest of winter wheat. Due to a summer monsoon climate with 70–80% of the mean annual rainfall (550 mm) occurring in the summer season (July to September), summer maize production is practically rain fed. The long-term effects of no-tillage can change the soil physical properties, soil fertility and moisture (Xu and Mermoud, 2001), but lead to greater soil bulk density and soil strength (Hammel, 1989; Ferreras et al., 2000). Little is known about the long-term effects of no-tillage on root growth and grain yield of summer maize in the North China Plain, and whether short-term of plow- and rotary-tillage based on no-tillage can promote root growth and grain yield.

The objectives of this study were to compare the effects of different tillage practices on spatial and temporal root growth, root-bleeding sap and nutrient uptake shortly after tilling, and to evaluate the relationships of root growth, nutrient uptake and grain yield responses to tillage practices during the summer maize growing season in the North China Plain.

2. Materials and method

2.1. Site description

Field experiments were conducted at the Wuqiao Experiment Station (37°41′ N, 116°37′ E) of China Agricultural University at Cangzhou, Hebei Province, China, in the 2011 and 2012 summer maize growing seasons. Winter wheat and summer maize is the main crop rotation system. The growing season of winter wheat is from early October to mid-June, and for maize from mid-June to later September. The same tillage practices were used with previous crop of winter wheat growing season in 2010 and continued the same tillage practices in the summer for maize growing season. Prior to initiation of the experiment, the tillage systems were rotary-tillage (RT) for winter wheat and no-tillage (NT) for summer maize in the double cropping system for 20 years. The average annual temperature is 12.9 °C with 201 frost-free days. Average annual rainfall is 562 mm, and more than 56% of the rainfall occurs during July–August. The soil of the field is light loam with 17.4 g kg^{-1} organic matter, 1.16 g kg^{-1} total N, 123.4 mg kg^{-1} available K and 41.2 mg kg^{-1} available P. Soil chemical data were measured at the beginning of the field experiments, while the soil bulk density and penetration resistance were measured at silking. A hand-held TJSD-750 model electronic cone penetrometer (Top, Hangzhou, Zhejiang, China) was used to measure the penetration resistance.

2.2. Crop management and experimental design

Summer maize (Zhengdan 958), a commonly used variety in Hebei Province, was sown manually on 18 June, 2011, and 12 June, 2012. Prior to planting maize, irrigation water (75 mm) was applied to guarantee the germination using the surface flood method through plastic pipe that was 50 mm in diameter. A completely randomized block design with five replications was used in the experiment. The plot size was 80 m^2 (8 by 10 m). In both years, all treatments received 124 kg N ha^{-1}, 138 kg P_2O_5 ha^{-1} and 56 kg K_2O ha^{-1}, before tillage. No fertilizer was applied during the growing season. Under no-till system (NT), fertilizers were placed in a narrow band using a hand hoe. The placement band was approximately 5 cm to the side and 5 cm below the seed-row zone. The fertilizers were broadcast by hand and then incorporated into the soil to a depth of 10 cm with secondary tillage using rotatory hoe under the rotary-tillage (RT) and plow-tillage (PT) systems.

Crop residues after wheat harvest were flattened and kept on the soil surface, and the only disturbance to the soil was during planting and fertilization application under NT. RT was done to 10 cm depth after winter wheat harvest with rotary tiller (1GKN-250, Yun gang xuan geng ji xie Co. Ltd., Lianyungang, Jiangsu, China), and wheat residues were incorporated into the soil. The rotary tool bar was equipped with a rotary blade spaced 75 cm apart and a set of finishing disks behind the blade for breaking large soil clods. The Moldboard plow involved complete soil inversion and burial of crop residue to a depth of 25 cm, by using 1L-220 model machine (Yili machine Co. Ltd., Yucheng, Shandong, China). The tillage width was set around 40 cm, followed by harrowing. Maize seeds were sowed by using the hand hoe for creating a trench of 5 cm deep for seed placement at 30 cm apart as in NT. The maize rows were 50 cm wide and the plant population in the tillage practices was 66,667 plants ha^{-1}. Weeds were controlled using 40% Propischlor–Atrazine suspoemulsion at the rate of 4.5 kg ha^{-1} after sowing.