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Response of maize root growth to irrigation and nitrogen management strategies in semi-arid loamy sandy soil

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ABSTRACT

Strategies to promote dense, deep root systems are important for the efficient use of water and nitrogen fertilisers in subtropical loamy sandy soil. This study assessed the effect of interactions between irrigation method (drip and furrow), irrigation level (full and reduced), and nitrogen fertiliser type (quick-release and slow-release) on root growth of maize (*Zea mays* L.) and the associated effect on grain yield, aboveground biomass and leaf area index. Factorial field experiments on semi-arid loamy sandy soil in Mozambique was carried out in four cropping periods (two in the hot-wet season, two in the cold-dry season). The response to the management factors at three growing stages of coarse (≥0.7 mm diameter) and fine (<0.7 mm diameter) root density (RD) (two cropping periods) and maximum rooting depth (four cropping periods) were measured in situ by modified profile wall method. The interactions between management factors did not explain the variation in maize RD or maximum rooting depth. However, seasonal variation between the cropping periods affected the distribution of coarse RD. Drip irrigation gave 33–153% higher coarse RD and 26–55% higher fine RD than furrow irrigation in deeper layers (16–64 cm), whereas furrow irrigation gave 21–40% higher coarse RD than drip at a shallow depth (0–16 cm). Irrigation level had little effect on RD, whereas slow-release fertilisation resulted in overall higher RD, aboveground biomass and grain yield than quick-release fertilisation in the cold-dry season. RD or maximum rooting depth showed few significant correlations with grain yield, biomass and leaf area index, respectively, but higher RD generally tended to result in higher yield. Overall, drip irrigation combined with reduced irrigation and slow-release N fertiliser appeared to be the most promising strategy to promote maize rooting and increase yield, especially in the cold-dry season.

1. Introduction

The development of an extensive root systems is critical for water and nutrient absorption by plants (Grabarnik et al., 1998; Yu et al., 2007; Nacry et al., 2013), contributing to increasing aboveground biomass accumulation (Wang and Smith, 2004; Li et al., 2009) and water and nutrient use efficiency (De Willigen and van Noordwijk, 1987). Good knowledge of root growth and structure is essential to match irrigation to crop requirements (Coelho and Or, 1999) since this determines the magnitude of water and nutrient uptake by crops (Dunbabin et al., 2003; Sampathkumar et al., 2012).

Small-scale irrigated agriculture in Mozambique is dominated by maize production (Bias and Donovan, 2003), which is the second most important staple food in the country after cassava (Donovan and Tostão, 2010). In general, approximately 48 kg nitrogen (N) ha^{-1} $year^{-1}$ are lost by leaching and erosion in traditional irrigated maize farming systems in Mozambique (Folmer et al., 1998). This is particularly the case in systems located in the south, with its predominantly sandy soils (Salman and Abdula, 1995; Nhantumbo et al., 2009), coupled with low water use efficiency (25–50%) in the widespread traditional furrow irrigation systems (FAO, 2005). Therefore, management strategies aimed at maximising root growth are essential to reduce water and nutrient losses and produce positive impacts on maize yield and N use efficiency.

A number of physical and chemical soil factors affect maize root distribution (Laboski et al., 1998; Coelho and Or, 1999), but soil

Abbreviations: CP-hw, cropping period during the hot-wet season; CP-cd, cropping period during the cold-dry season; D, drip irrigation; F, furrow irrigation; FC, field capacity; I_f, full irrigation to meet at least the crop water requirements; I_r, reduced irrigation (75% of I_f); N_q, quick-release nitrogen fertiliser; N_s, slow-release nitrogen fertiliser; RD, root density (number of roots 100 cm^{-2}); WP, wilting point.

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water conditions (Laboski et al., 1998) and nutrient levels (Skinner et al., 1998) are the most crucial factors. Given the high N demand in maize, the key strategy in sandy soils is to create a good balance between N fertiliser and water availability (van Vuuren et al., 1996; Sangakkara et al., 2010; Benjamin et al., 2014).

A number of studies examining the impact of isolated or combined effects of irrigation methods, irrigation levels and N fertilisers on root distribution under different conditions have greatly advanced understanding of these issues (*e.g.* Coelho and Or, 1999; Sampathkumar et al., 2012; Trachsel et al., 2013; Wang et al., 2015). Accordingly, under irrigated conditions, maize root system was reported to be confined to shallow depths (upper 30 cm) in cases of naturally occurring compact layers (Laboski et al., 1998) or, additionally, early N imbalances (excess or deficiency) (Peng et al., 2012), the latter indicating the importance to synchronise N application to match maize N demand. Moreover, the deepening and expansion of root systems in sandy soils have been reported to be stimulated by increased water stress in the soil profile (Sampathkumar et al., 2012; Zhang et al., 2014). Contrastingly, Gao et al. (2010) reported deeper penetration of maize roots under well wetted conditions. In cultivation with limited soil moisture, furthermore, maize roots have been found to become thinner ($\leq$0.5 mm in diameter), especially under high plant density and sufficient fertilisation (Wang et al., 2015).

Slow-release N fertilisers are known to promote a more homogeneous nutrient distribution in the soil (Lucas et al., 2011), offering a viable alternative for sustainable productivity when synchronised with the physiological needs of maize plants (Sharma and Singh, 2011; Guan et al., 2014a,b). A study on the morphological and physiological responses of rice roots to application of slow-release fertiliser revealed an increase in root dry weight, total root length and root volume. As a result, this promoted a rise in grain yield. Moreover, root system growth should allow maximisation of water and nutrient use efficiency, thus reducing N leaching below the root zone. In sandy soils, for example, rapid production of high root density in the topsoil during early development stages, followed by vigorous taproot growth, has been reported as crucial for deep water and N retrieval, contributing to a reduction in N leaching (Dunbabin et al., 2003).

The number of comparative studies on maize root growth under different management practices is still inadequate (Wang et al., 2015), especially with regard to the response to interactions between various new irrigation and N management strategies. Therefore, the objective of the present study was to assess the degree of maize root response (density and maximum rooting depth) to interaction of two irrigation methods, two irrigation levels and two top-dressing N fertiliser types in experimental plots on loamy sandy soil in southern Mozambique. The effect of season on root response, as well as the relationship between root density or maximum rooting depth and each of maize yield, biomass and leaf area index (LAI) was also investigated. The starting hypothesis was that maize root density and maximum rooting depth are increased by a combined application of drip irrigation, reduced irrigation level and slow-release N fertiliser (enhanced practices) compared with furrow irrigation, full irrigation level and quick-release N fertiliser (conventional practices). It was assumed that this increase in root density would benefit grain yield, aboveground biomass and LAI.

2. Materials and methods

2.1. Site description and weather data

The field experiments were carried out on the experimental station of the Faculty of Agronomy and Forestry Engineering in the village of Sábie, southern Mozambique (25°19′13″S; 32°15′53″E, 58 m above sea level) from 2012 to 2015. In general, the site is characterised by a tropical steppe climate, corresponding to BSh in the Köppen classification (Peel et al., 2007), with two distinct seasons: a hot-wet season from October to April and a cold-dry season from May to September (Reddy, 1984). Mean annual temperature is 23 °C, with a mean minimum of 11 °C in June and July and a mean maximum of 34 °C in December and January. Mean annual rainfall is 580 mm and shows a strong seasonal variation, with about 88% falling in the hot-wet season and the remaining 12% in the cold-dry season (Reddy, 1984). Average annual potential evapotranspiration is 1500 mm, with June and July having the lowest values of approximately 100 mm (Reddy, 1986).

The soils at the experimental station comprise deep stratified alluvial deposits, with slope of 1–2%, classified as Eutric Fluvisols (FAO soil classification) (INIA, 1990) and had been under bush fallow for 10 years before the start of the first cropping period. Soil samples collected in the upper 90 cm throughout the experimental site, before the first cropping period, revealed that the soil texture ranged from loamy sand to sandy loam in the different soil layers, total N concentration was between 0.02 and 0.18% (w/w) and organic matter concentration was between 0.07 and 2.08% (w/w), while total available N ranged from 15.5 to 43.6 kg ha^{-1}. A single soil profile pit excavated at the site to 160 cm revealed mean dry bulk density values ranging between 1.18 and 1.44 g cm^{-3}, field capacity (at pF 2) between 14.7 and 24.4% (v/v) and permanent wilting point (pF 4.2) between 3.9 and 5.8% (v/v).

2.2. Layout and experimentation

A maize crop (*Zea mays* L.) was first planted and monitored during the cropping period November 2012–February 2013 in the hot-wet season (CP-hw1) and thereafter in May-September 2013 in the cold-dry season (CP-cd1), matching the two annual growing seasons. A full description of the site characteristics and experiments for these two cropping periods can be found in Chilundo et al. (2016). A second set of experiments was conducted at the same site and plots in the following cold-dry season, May–September 2014 (CP-cd2), and in the hot-wet season, November 2014–February 2015 (CP-hw2), in order to verify the results obtained in the first set of experiments.

The layout of the experiment was similar for all cropping periods and included eight treatments, resulting from the combination of two irrigation methods, two irrigation levels and two top-dressing N fertiliser types arranged in a 2 × 2 × 2 factorial system in a randomised complete block design with three replicates. The irrigation methods were furrow (F) and drip (D); irrigation levels were to meet at least the full crop water requirements (crop evapotranspiration in Eq. (1)) (I_f) and reduced irrigation at 75% of I_f (I_r); and the N fertiliser types were quick release (N_q) and slow release (N_s). The treatments assigned to each plot were DI_fN_s, DI_rN_s, DI_fN_q, DI_rN_q, FI_fN_s, FI_rN_s, FI_fN_q and FI_rN_q.

The size of each individual plot was 8 m × 8 m. The three blocks were separated by a 2 m-wide strip, while a 1-m strip separated the individual plots. Each plot consisted of nine rows of maize with a spacing of 80 cm between each row. Medium maturation maize hybrid PAN67, which has a cycle of approximately 110 days to maturation in the hot-wet season and 140 days in the cold-dry season, was planted manually, with 30 cm spacing between plants and a density of 41600 plants ha^{-1} in all plots, on 10 November in CP-hw1 and CP-hw2, and on 10 May in CP-cd1 and CP-cd2. Maize was harvested on 10 March in CP-hw1 and CP-hw2 and on 10 October in CP-cd1 and CP-cd2. Pests were controlled by spraying chemicals according to recommendations by UDA (1982) and weeds were controlled manually by hoeing.

During CP-cd2, at the transition from the six-leaf (V6) to seven-leaf (V7) stage, maize plants were accidentally defoliated at the