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Effect of irrigation regimes and nitrogen rates on water use efficiency and nitrogen uptake in maize

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ABSTRACT

The nutritional responses to drying and rewetting cycles of partial root-zone irrigation still remains elusive. The effect of alternate partial root-zone irrigation (PRI) on water use efficiency and nitrogen (N) accumulation compared with deficit irrigation (DI) and full irrigation (FI) were investigated in maize (*Zea mays* L.) grown under three N-fertilization rates (1.5, 3.0, and 6.0 g N pot^{-1}) and moderately and severely water-stressed levels (60 and 40% of soil water holding capacity). The plants were grown in split-root pots and exposed to FI, DI and PRI treatments from the fourth leaf to silking stage. Analysis across the N-fertilization treatments showed that both PRI and DI significantly decreased plant water use as well as plant height, stem girth, leaf area and shoot biomass, leading to similar WUE compared with the FI control. Carbon isotope composition ($\delta^{13}C$) was highest in PRI plants indicating a fine-tuned long-term stomatal control over gas exchange. Across the N-fertilization rates, FI plants accumulated significantly greater amount of N than deficit irrigation treatments. PRI and DI plants had similar plant $\delta^{15}N$, indicating the similar soil N mineralization. Plant dry biomass, which was linearly associated with plant N uptake, was similar for PRI and DI plants. Both resulted in the equivalent amount of N accumulation in the shoots of PRI and DI plants. It was noted that increased soil moisture level, e.g., from 40% to 60%, showed the tendency of increasing N uptake for PRI plants relative to DI plants. Therefore, in order to facilitate N uptake, soil water availability in the wet soil compartment of PRI treatment should remain at high water levels.

1. Introduction

Water is the most limiting factor in reducing crop productivity particularly on the 40% of global land under arid or semi-arid climatic conditions where irrigation is the only way to maintain a stable food production (Cattivelli et al., 2008). Increasing threats of freshwater shortage, reduction in arable land, and more frequent and severe drought due to climate change has stimulated research into water-saving irrigation strategies aiming at producing more ‘crop per drop’ (Morison et al., 2008; Dodd, 2009). Deficit irrigation (DI) and partial root-zone irrigation (PRI) are water-saving irrigation techniques being intensively studied in many regions of the world. DI is a method that irrigates the entire root zone with an amount of water less than the potential evapotranspiration and the minor stress that develops has minimal effects on the yield and thereby increases water use efficiency (WUE) (English and Raja, 1996). PRI is a further refinement of DI. The principle behind PRI is to alternately let one part of the root system be exposed to soil drying, while the other part is irrigated, in order to keep the leaves hydrated. It is widely believed that one of the underlying mechanisms for improved WUE under PRI is the induced abscicic acid (ABA) based root-to-shoot chemical signalling in the drying roots which causes partial closure of stomata and reduction of leaf expansion growth thereby curtailing the transpirational water loss (Davies et al., 2000; Liu et al., 2006; Dodd, 2007; Wang et al., 2010a).

When applying DI or PRI soil water dynamics are changed being more ‘static’ under DI than under PRI and this has influenced both plant physiological and soil water and nutrient mineralization processes (Wang et al., 2010a,b; Wang et al., 2012a,b,c). Until now, there has been considerable discussion in the literature regarding the regulation of chemical and hydraulic signals on stomata and plant growth under DI and PRI (reviewed by Dodd, 2009; Sadras, 2009; Jensen et al., 2010). A knowledge gap, however, still exists on the nutritional responses to drying and rewetting cycles under soil water dynamics by PRI (Dodd et al., 2015; Wang et al., 2016).

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We have observed that, with the same degree of water saving, PRI-treated tomatoes accumulated greater amount of N in shoots compared to DI plants, which partly contributes to the greater WUE in PRI plants (Wang et al., 2010a). Using the ^{15}N isotope labeling technique, it was found that PRI induced dry/wet cycles in the soil stimulated mineralization of organic N hence increasing the amount of mineral N available for plant uptake (Wang et al., 2010b). The effect of increase in soil water dynamics caused by PRI on plant N nutrition is shown in several additional studies. In maize, Kirda et al. (2005) reported that PRI had the highest N-fertilizer recovery, compared with DI and FI, with minimal mineral N residues left in the soil after harvest. Wang et al. (2012a) found significantly higher N accumulation in maize leaves compared with DI and FI treatments. Likewise, Wang et al. (2009) noted that in relation to DI, PRI increased N content in all organs of potato plants. Liu et al. (2015) reported that PRI plants accumulated 23% and 34% more N than DI plants under the treatments with and without P fertilization, respectively. However, Topcu et al. (2007) found no significant differences in N accumulation and fertilizer recovery of tomato plants among FI, DI and PRI treatments. In potatoes, Shahnazari et al. (2008) reported that N accumulation was similar between PRI and DI treatment. Li et al. (2007) found similar shoot N accumulation in PRI treatment compared to conventional irrigation in maize plants. Therefore, more studies are still necessary to examine further whether PRI can improve crop N accumulation in order to fully exploit the beneficial effect of the irrigation technique in crop production.

Carbon isotope composition ($\delta^{13}C$) in plant biomass provides a time-integrated measurement of plant WUE under water stress (Farquhar and Richards, 1984). A greater $\delta^{13}C$ is always positively associated with higher WUE, and this has been extensively used for many C_3 and C_4 plants including maize (Dercon et al., 2006; Zhang et al., 2015). Plant ^{15}N has been widely used to indicate the mineralization rate of soil organic N as soil microbes discriminate against ^{15}N during mineralization and immobilization turnover process, leaving soil organic N enriched in ^{15}N (Kerley and Jarvis, 1996). Therefore, plants grown in soils relying on more N derived from soil organic N pool should be enriched in ^{15}N in the biomass than the plants obtaining N mainly from inorganic N (Kohl et al., 1973). The objective of the present study is to investigate the effect of irrigation regimes and nitrogen rates on water use efficiency and nitrogen uptake in maize.

2. Materials and methods

2.1. Experimental setup

The pot experiment was conducted in April-June, 2013 under a rain shelter with natural light and temperature conditions at the experimental farm of Department of Agricultural Engineering, Kwame Nkrumah University of Science and Technology (KNUST), Kumasi, Ghana, (06°41′N, 01°33′W). The climate in this area is humid tropical savannah with average maximum and minimum temperatures of 31 °C and 23 °C, respectively, during the experimental period. At the third leaf stage, maize plants (*Zea mays L.*) were transplanted into pots (28 cm in diameter at the top edge, 25 cm in diameter at the bottom, 32 cm in depth) filled with 19.0 kg of naturally air-dried soil per pot with a bulk density of 1.2 g soil cm^{-3}. Before filling the pots, the soil was sieved passing through 1 cm mesh. The inside of all pots was evenly divided into two vertical compartments by a plastic seperator which was glued to the walls of the pots such that water exchange between the two compartments was prevented. The bottoms were perforated with small holes which allow free drainage. The soil was classified as sandy loam, having a pH of 6.2, total N of 1.4 g kg^{-1}, total P of 0.7 g kg^{-1}, total K of 15.8 g kg^{-1}, soil organic matter content of 5.7% and soil water holding capacity of 19% (on the mass basis). The natural ^{15}N-abundance of the soil N was 0.368% (i.e., $[^{15}N:(^{14}N + ^{15}N)]\%$). Plants were placed at the middle of the pots so that their primary roots were fairly evenly distributed into the two compartments of pots.

2.2. Irrigation and N-fertilization treatments

Treatments comprised two levels of soil moisture, three irrigation methods and three N-fertilization rates. The soil moisture regime was either 60% or 40% of soil water holding capacity (θ_{WHC}), representing moderately or severely water-stressed conditions. Soil water content regime was controlled by weighing the pots and irrigating the plants during the experimental period. Irrigation methods include (1) DI in which soil compartments were irrigated to 60 or 40% of θ_{WHC} in each irrigation event; (2) PRI in which one soil compartment was watered with exactly the same amount as the DI treatment, while the other was allowed to dry for about 8 days, then the irrigation was shifted to the other soil compartment; (3) FI as a well-watered control treatment in which both of the soil compartments were watered to 80% of θ_{WHC} in each irrigation event. Three N-fertilization rates included low N (N1, 1.5 g N pot^{-1}), medium N (N2, 3.0 g N pot^{-1}) and high N (N3, 6.0 g pot^{-1}). The experimental plan yielded 15 treatments (i.e. $2 \times 2 \times 3 + 3 \times 1$), with four replicates in each treatment. At the commencement of the experiment, 1.5 g N pot^{-1}, 0.65 g P pot^{-1}, and 1.25 g K pot^{-1} was applied in the form of commercial granulated NPK-fertilizer into the surface layer of pots. Additional urea-N was applied for the medium and high N treatments with irrigation water just before the initiation of irrigation treatments. The maize plants were well-watered in the first 10 days after transplanting, and then the water treatments were initiated. Water was applied every second (0–24 days after irrigation treatment (DAT)) or every day (25–51 DAT). The experiment lasted seven weeks, during which each soil compartment of PRI-treated plants experienced six drying/rewetting cycles.

2.3. Sampling, measurements and analysis

The plants were harvested on 19th June at 51 DAT. Plant height, stem girth, leaf length and width were measured by a flexible measuring tape. Leaf length was defined as the distance from the tip of the leaf to the branching point of the main vein. Leaf width was measured as the widest region across the lamina perpendicular to the length. Leaf area was estimated by multiplying leaf length, leaf maximum width and a constant (0.73) (Stewart and Dwyer, 1999). Leaves, stems, reproductive organs (including tassels and young ears) were harvested separately. Dry biomass was determined after oven drying at 70 °C to constant weight.

After grinding in a ball mill, the plant samples were analysed for total N, ^{15}N, total C, and ^{13}C content using the Dumas dry combustion method in a system consisting of an ANCA-SL Elemental Analyser coupled to a 20–20 MassSpectrometer (Sercon Instruments, Crewe, UK). Natural $\delta^{15}N$ in plant biomass was calculated as:

$$\delta^{15}N = [(R_{sample} - R_{standard})/R_{standard}] \times 1000$$

where R_{sample} and $R_{standard}$ are the $^{15}N:(^{14}N + ^{15}N)$ ratios of the plant sample and the standard, respectively. The carbon isotope composition of plant samples was calculated as:

$$\delta^{13}C = [(R_{sample} - R_{standard})/R_{standard}] \times 1000$$

where R_{sample} is the $^{13}C/^{12}C$ ratio of the sample and $R_{standard}$ is the $^{13}C/^{12}C$ of the PDB (Pee Dee Belemnite) standard. $\delta^{13}C$ was used as an indicator of the integrated long-term WUE. Crop water