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Effects of reduced irrigation dose and slow release fertiliser on nitrogen use efficiency and crop yield in a semi-arid loamy sand

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ABSTRACT

Quantification of the interactive effects of irrigation water and nitrogen (N) fertiliser on nitrogen use efficiency (NUE) provides an important insight for more effective water and N management. This study evaluated the effects of different irrigation and N fertiliser management options on water flux, N uptake, NUE and maize grain yield in a semi-arid loamy sand in Mozambique. The experiments were carried out in field plots in two consecutive cropping periods (CP's) representing contrasting growing seasons: a hot-wet season (CP-1) and a cold-dry season (CP-2). The treatments included two irrigation methods (furrow and drip), two irrigation levels (75 and 100% of the crop water requirement), and two distinct N fertiliser types (a quick-release and slow-release urea) arranged in a randomised complete block design. In both CP-1 and CP-2, NUE tended to be higher for the 75% irrigation level, regardless of irrigation method and N fertiliser type. Higher NUE was generally observed in CP-2 than in CP-1. The highest grain NUE (41.6 kg kg^{-1} N) was observed in CP-2 under furrow irrigation combined with 75% irrigation level and quick-release N fertiliser. Slow-release N fertiliser did not improve N uptake, NUE or maize yield. Potential N losses were assumed to be higher in CP-1 than in CP-2, associated with higher estimated deep percolation volumes in CP-1 (mean 127 mm) than in CP-2 (mean 12 mm). In CP-1, deep percolation events mainly coincided with high rainfall events. Furrow irrigation tended to give higher NUE than drip irrigation, especially in CP-2. Reducing of irrigation level by 25% tended to increase N uptake, NUE and maize yield for both CP-1 and CP-2. The effects of slow-release N fertiliser and drip irrigation were inconclusive.

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1. Introduction

Maize is a staple crop in Mozambique, contributing more than 27% of gross domestic product (Bias and Donovan, 2003), and is typically managed with low nitrogen (N) fertiliser inputs (AGRA, 2013). However, large quantities of irrigation water are applied, posing risks of N losses, especially as the N fertiliser application rate is expected to reach at least 50 kg N ha^{-1} by 2015 (Eilittaä et al., 2006). This is a particular concern in semi-arid irrigated areas of Southern Mozambique receiving less than 400 mm rainfall per year (Reddy, 1986), which are dominated by maize in both cropping seasons.

Low water use efficiency (about 25–50%) in the predominant furrow irrigation management (FAO, 2005), coupled with predominance of sandy soils (INIA, 1994; Salman and Abdula, 1995; Nhantumbo et al., 2009), are reported to be the major factors limiting irrigated maize yield in Mozambique (<1.5 t ha^{-1}) (Bias and Donovan, 2003). Together, these poor water and nitrogen use efficiencies call for new strategies to achieve sustainable maize production in the country (Bias and Donovan, 2003).

Modern and best management practices that synchronise water use, N availability and uptake in order to increase nitrogen use efficiency (NUE) have been evaluated (Diez et al., 1997; Li et al., 2007; Djaman et al., 2013). The results led Li et al. (2007) to suggest a combination of suitable irrigation methods and levels with split application of N fertilisers or application of slow-release N fertilisers. Other studies have focused on irrigation management strategies to improve water productivity, NUE and maize yields, either by evaluating alternative irrigation methods (Al-Jamal et al., 2001; Pereira et al., 2002; Zotarelli et al., 2008; Hassanli et al., 2009; Tagar et al., 2012) or by using reduced irrigation level (Doorenbos and Kassam, 1979; Farré and Faci, 2009; Gheysari et al., 2009b; Mansouri-Far et al., 2010; Steduto et al., 2012). Although some positive results were obtained, a lower maize response when exposed to reduced soil moisture was reported, reflecting the close relationship between available soil moisture and N uptake.

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Table 1
Physical properties at the experimental site in Sábie, based on samples obtained by augering the central part of each plot (texture% by weight) (mean ± standard deviation; $n = 24$) and on duplicate core samples collected in a pit (water retention% by volume, bulk density and particle density g cm^{-3}).

Depth (cm)	Soil properties						
	Sand [%]	Silt [%]	Clay [%]	Water retention (%) Field capacity [1 m]	Wilting point [150 m]	Bulk density [g cm^{-3}]	Particle density [g cm^{-3}]
0–20	80.7 ± 4.0	9.2 ± 2.6	10.2 ± 1.8	21.9	5.78	1.42	2.63
20–40	81.6 ± 2.6	8.2 ± 2.2	10.2 ± 1.7	19.3	5.19	1.31	2.65
40–60	80.7 ± 2.1	8.6 ± 1.6	10.7 ± 1.6	22.6	5.61	1.30	2.64
60–80	80.1 ± 2.6	9.3 ± 2.1	10.6 ± 1.5	19.0	5.01	1.34	2.66

Application of slow-release N fertiliser as a key strategy to increase NUE has also been addressed in a number of studies (Shaviv and Mikkelsen, 1993; Díez et al., 1994; Shaviv, 2005; Nelson et al., 2009). For example, Zvomuya et al. (2003) showed a potential increase in NUE using coated urea, by reducing the fraction of N lost to deeper layers by 34–49%. Additionally, Díez et al. (1994) showed that over 100 kg N ha^{-1} were lost to the groundwater aquifer when normal quick-release urea was applied at a rate of 294 kg N ha^{-1} in maize experiments, whereas losses were reduced by 37.7% (63 kg N ha^{-1}) when Floranid 32, a slow-release N fertiliser, was applied. Similar findings were made by Wilson et al. (2010).

The effects of different combinations of water and N management options on maize performance, with particular emphasis on N uptake and NUE, and a consequent evaluation of alternative management strategies have been widely addressed (e.g., Díez et al., 1994; Balík et al., 2003; Çakir, 2004; Bahr et al., 2006; Li et al., 2007; Barbieri et al., 2008; Hu et al., 2008; Berenguer et al., 2009; Hassanli et al., 2009; Gheysari et al., 2009a). However, given the limited information available for tropical/subtropical and developing countries (Riley et al., 2001) and the fact that the best combinations of management strategies are site-specific (Shrestha et al., 2010), more research is needed to define better management strategies in these areas. This is particularly important for farming systems in Southern Mozambique, where increased maize yield has to be coupled with strategies to reduce water and N losses, and consequently increase NUE.

The aim of the present study was to assess the effects of different irrigation strategies and N fertiliser types on soil water N, N uptake by maize plants, NUE and yield during two contrasting cropping seasons on a semi-arid loamy sand in Southern Mozambique. The findings were intended to help identify suitable combinations of water and N practices that will improve maize yields and NUE in semi-arid cropping systems of Southern Mozambique.

2. Material and methods

2.1. Experimental site

Field experiments were established at the Faculty of Agronomy and Forestry Engineering experimental station in Sábie village, Southern Mozambique (25°19′1″S; 32°15′53″E, 58 m above sea level) in 2012 and 2013.

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. 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 distribution, with about 88% falling in the hot-wet season and the remaining 12% in the cold-dry season. Annual potential evapotranspiration frequently exceeds 1500 mm, with June and July having the lowest values (100 mm) (Reddy, 1986).

The soils at the experimental station comprise deep stratified alluvial deposits, with slopes of 1–2% (INIA, 1994), and have been under bush fallow for the past 10 years. Deep loamy sand to sandy loam soils dominate (>4 m deep), with the 0–20 cm layer consisting on average of 80.7% sand, 9.1% silt and 10.2% clay, with bulk density 1.42 g cm^{-3} and particle density 2.63 g cm^{-3} (Table 1). The nutrient status of the soil, determined according to procedures described by Westerhout and Bovee (1985), is shown in Table 2. The antecedent mineral nitrogen content (NO_3^--N and NH_4^+-N) before the two seasons, determined by titration after extraction with 1 M KCl (Bremner, 1960), is shown in Table 3.

2.2. Experimental design

Two consecutive and contrasting cropping seasons, matching the two annual seasons, were studied. The first cropping period (CP-1) ran from November 2012 to February 2013, i.e., during the hot-wet season and the second cropping period (CP-2) from May to November 2013, i.e., during the cold-dry season. The experiment layout for both CP-1 and CP-2 consisted of eight treatments, resulting from a combination of two irrigation methods, two irrigation levels and two types of topdressing N fertilisers arranged in a 2 × 2 × 2 factorial system in a randomised complete block design with three replicates. The area of each individual plot was 8 m × 8 m (Fig. 1). The blocks were separated by a 2 m wide strip, while a 1 m strip separated the individual plots. Medium maturation PAN67 maize hybrid was planted at 80 cm × 30 cm spacing in all plots.

2.3. Irrigation regime

Throughout CP-1 and CP-2, water from the Incomati River was used for the irrigation. Mean monthly water quality data (NO_3^--N, NO_2^--N and NH_4^+-N) were taken from Moamba monitoring station located 28 km upstream from the experimental site. Two irrigation methods (furrow irrigation (F) and drip (D) irrigation) were combined with two irrigation levels (100% (L_{100}) and 75% (L_{75}) of estimated crop water requirements). Volumetric flow meters were used to control irrigation level, attached to a flexible hose for F plots and installed on the irrigation manifold pipes for D plots (Fig. 1). Before sowing CP-1, 40 mm of rainfall fell and thoroughly wetted the soil. In order to establish equivalent antecedent soil moisture conditions in CP-2, which was fairly dry before sowing, 40 mm were applied as irrigation water. Throughout the first 15 days after sowing in CP-1, all plots were irrigated with the same level. In CP-2, the occurrence of fungus disease affected the entire experiment, forcing irrigation to be extended to the first 33 days after sowing to avoid additional stress. Thereafter, the specific water treatments L_{75} or L_{100} were applied.

A modified version of the water balance equation by Allen et al. (1998) was used to determine the irrigation timing through calculation of daily soil water deficit in the soil, i.e.,

$$D_{r,i} = D_{r,i-1} + ET_{c,i} - I_{r,i} - P_i$$

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