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Maize water use efficiency and evapotranspiration response to N supply under contrasting soil water availability

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ABSTRACT

Water use efficiency (WUEg), the quotient between grain yield and crop evapotranspiration (ET), might be increased in maize crops (*Zea mays* L.) due to N supply. Most research has focused on understanding grain yield response to N supply; so there is little and contradictory information on the influence of N supply on WUEg in water limited environments and on ET response to N supply under contrasting water availability. The objectives of our research were to elucidate whether N supply affects WUEg in water limited environments; and to clarify the expected response to N supply of maize ET and its components under contrasting soil water availability. Maize crops were grown at Balcarce, Argentina during three seasons. Treatments included two water regimes (i.e. rain-fed and irrigated) and two rates of N (i.e. 120 kg N ha^{-1} or non-fertilized). Measurements included (i) soil water content and intercepted photosynthetically active radiation (iPAR) during the whole crop season, and (ii) grain yield and shoot dry matter at physiological maturity. Crop ET was calculated by means of a water balance and soil evaporation was estimated by means of micro-lysimeters. Our results show that N supply did not influence WUEg in water limited environments; but N supply significantly increased ET (2–8%) under all water availability conditions. Maize seasonal ET increments were closely related to the improvement of seasonal iPAR in non-water limited environments, but not in water limited environments. In non-water limited environments, ET response to N supply was mediated by the concomitant effects of iPAR increments on increasing transpiration while reducing evaporation. In water limited environments, ET slightly increased in response to iPAR increments due to N supply. The low ET increment in water limited environments with frequent low superficial soil water content (i.e. $\leq$2 mm cm^{-1}) was probably not influenced by reductions in evaporation (E); but associated with stomata closure in response to water deficiencies. This is consistent with the fact that N supply did not promote improvements in radiation use efficiency for biomass production (RUEb) in these environments.

1. Introduction

Water availability often limits grain yield of rain-fed crops; and 12–15% grain yield reductions due to water stress were estimated for maize grown in temperate regions (Edmeades et al., 2001; Eyhérabide et al., 1996). In addition, it is expected that dry periods will become more frequent due to climate change (Solomon et al., 2007). In this context, ways to increase crops water use efficiency (i.e. grain yield per unit of evapotranspiration, WUEg) should be sought. Management practices like mulching (e.g. Zhang et al., 2014), row spacing reductions (Barbieri et al., 2012) and N supply (e.g. Viets, 1962; Ogola et al., 2002), among others, have the potential for increasing WUEg in maize and in other crops (Hatfield et al., 2001; French and Schultz, 1984).

It is well known that N supply increases grain yield and WUEg in N deficient soils with no water limitations (e.g. Olson et al., 1964; Eck, 1984; Kim et al., 2008; Al-Kaisi and Yin, 2003; Di Paolo and Rinaldi, 2008). In these environments, grain yield increments due to N supply were mainly related to shoot biomass increments, by means of (i) greater photosynthetically active radiation interception (iPAR; e.g. Wolfe et al., 1988; Bennett et al., 1989; Uhart and Andrade, 1995; Sinclair and Muchow, 1999; Boomsma et al.,

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2009); and (ii) greater radiation use efficiency (RUEb; e.g. Sinclair and Muchow, 1999; Boomsma et al., 2009). However, there is little information and conflicting results on the influence of N supply on the evapotranspiration (ET) component of WUEg. Some reports indicate that in non-water limited environments, N supply increased ET (Pandey et al., 2000; Ogola et al., 2002; Abbas et al., 2005; Adamtey et al., 2010; Barbieri et al., 2012) or there was not a clear trend in ET response to N supply (Reddy et al., 1980; Jones et al., 1986; Fernández et al., 1996; Kim et al., 2008; Teixeira et al., 2014).

In water limited environments, grain yield and WUEg response to N supply will be closely associated with the timing and intensity of the water and N deficiencies. Water deficiencies reduce shoot biomass production through reductions in iPAR (Jones et al., 1986; Wolfe et al., 1988) and/or RUEb (Stone et al., 2001). In addition, water deficiencies during the critical period for kernel set (i.e. 30 days bracketing silking) drastically reduce grain yield through reductions in harvest index (HI; Hall et al., 1981). These responses to water deficiencies might decrease N supply effects on biomass production and grain yield. In agreement, some reports have demonstrated that N supply does not increase grain yield in water limited environments (Eck, 1984; Kim et al., 2008; Di Paolo and Rinaldi, 2008), suggesting that N supply does not increase WUEg in these environments. By contrast, other papers indicate that N supply increased maize WUEg in dry environments (e.g. Ogola et al., 2002; Teixeira et al., 2014); or proposed that management practices (including N fertilization) that affect biomass production or the interception of radiation may increase WUEg under contrasting water availability (Hatfield et al., 2001). However, most of the studies dealing with maize grain yield response to N supply under different water regimes do not include crop ET measurements. The few reports accounting for maize ET in water limited environments indicated none (Ogola et al., 2002; Teixeira et al., 2014), 6% (Barbieri et al., 2012), or more than 60% crop ET increment (Jones et al., 1986; Pandey et al., 2000; Abbas et al., 2005) in response to N supply. Therefore, reports on the role of N supply on crop ET and on WUEg in water limited environments are scarce and not consistent, highlighting the need of a greater understanding of the N supply × water regime interaction.

Crop ET response to N supply will be the result of N effects on its components, crop transpiration (T) and soil evaporation (E). Soil water availability, iPAR and RUEb affect transpiration (Jones et al., 1986; Matthews et al., 1988; Earl and Davis, 2003); whereas the degree of soil cover by the crop and superficial soil water content are the primary factors influencing E rates from soil beneath crop canopies (Ritchie and Burnett, 1971; Ritchie, 1972; Villalobos and Fereres, 1990; Allen et al., 1998). In environments with low soil water content that limits evaporation (Ritchie, 1972; Villalobos and Fereres, 1990), ET response to N supply will mostly depend on transpiration response to N supply; whereas in non-water limited environments, ET response to N supply will be mediated by both, an increased transpiration and a reduced evaporation.

The objectives of this work were (i) to elucidate whether N supply affects WUEg in water limited environments, and (ii) to clarify the expected response to N supply of maize ET and its components under contrasting soil water availability.

2. Materials and methods

2.1. Site and crop management

Maize crops were grown at Balcarce, Argentina (37°45′ S, 58°18′ W; elevation 130 m), during 2011–2012 (Season1), 2012–2013 (Season 2) and 2013–2014 (Season 3). The soil was a complex of a fine mixed Typic Argiudoll and a fine thermic Petrocalcic Paleudoll (petrocalcic horizon at 140 cm), with a loam texture at the surface layer (0–25-cm depth), loam to clay-loam at sub-surface layers (25–110-cm depth) and sandy-loam below 110-cm depth (C-horizon) with 5.4% topsoil organic matter. Maximum water holding capacity (3.7 mm cm^{-1}) was determined according to Cassel and Nielsen (1986) and the permanent wilting point (2 mm cm^{-1}) was determined according to Richards and Weaver (1943). Experiments were conducted under conventional tillage. Crops were fertilized with 30 kg P ha^{-1} before sowing. Weeds and insects were effectively controlled. The location of the plots and treatments during Seasons 2 and 3 corresponded with those during Season 1; and initial mean soil N-NO_3^- in non-N fertilized plots were 101 ± 8.6 (Season 1), 99 ± 7.8 (Season 2) and 94 ± 7.3 kg ha^{-1} (Season 3) for the top 60 cm at sowing. Local studies indicated that grain yield responses to N supply are expected at these soil N-NO_3^- contents at sowing (Echeverría and Sainz Rozas, 2001) and thresholds of 177 kg ha^{-1} of N-NO_3^- (0–60 cm) to attain maximum grain yields were reported for no-till maize in the same location (Pagani et al., 2008).

Cumulative photosynthetically active radiation and mean air temperature during the growing seasons were close to the mean value for a series of 30 years (Table 1). Water input from rain accumulated from emergence to physiological maturity was 387 mm in season 1, 588 mm in Season 2, and 364 mm in Season 3; and water input distribution along the growing season differed among years (Table 1 and Fig. 1). In addition, reference ET accumulated from emergence to physiological maturity was 631 mm in Seasons 1 and 3 and 614 mm in Season 2. Consequently, rain-fed treatments of Seasons 1 and 3 were considered water limited environments; and irrigated and rain-fed treatments of Season 2 and irrigated treatments of Seasons 1 and 3 were considered non-water limited environments.

2.2. Plant material and experimental design

Maize hybrid DK 747 MGRR was sown on 25 Oct, Seasons 1 and 2 and on 18 Oct, Season 3. Treatments included two water regimes (rain-fed and irrigated) and two rates of N supply (0 and 120 kg N ha^{-1}). Maize plant density was 8 plants m^{-2}; plots were over-sown and thinned to the desired plant densities at V3 (Ritchie and Hanway, 1982). The treatments were arranged in a split plot design with three replications; irrigation treatments were assigned to the main plots and fertilizer treatments were assigned to the sub plots. Sub plots comprised five rows 12 m long. Drip irrigation was performed to maintain soil water availability above 60% of soil available water during the growing cycle. Although irrigation was applied, it was not effective at maintaining soil water content above this value during Seasons 1 and 3. Fig. 1 indicates moments and amounts of irrigation for the different treatments. Fertilized treatments received 120 kg N ha^{-1} at V6 in Seasons 1 and 2 and at sowing in Season 3; N was applied broadcast in the three seasons.

2.3. Measurements

Soil water content was measured with a neutron probe (Troxler Electronic Lab., Troxler 4300, NC, USA) in each experimental unit from 12 (Seasons 1 and 2) or 13 days (Season3) after emergence until physiological maturity. The method combined gravimetric measurements between 0 and 10 cm depth and the use of the neutron probe in 10 cm increments between 10 and 40 cm depth and in 20 cm increments from 40 to 140 cm depth. Total soil water content in each experimental unit was determined as the sum of the water content in all layers. One access tube per experimental unit was placed midway between the two harvest rows and soil water was measured approximately every 7–15 days.