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Water use efficiency for grain yield in an old and two more recent maize hybrids

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ABSTRACT

Increasing water use efficiency for grain production, WUEg (i.e. the quotient between grain yield and seasonal evapotranspiration, ET) is of relevance in rainfed crops. A greater WUEg is expected in more recent than in old maize (*Zea mays* L.) hybrids, based on different reports indicating higher grain yield, higher stress tolerance or similar seasonal ET in more recent than in old maize hybrids. However, there are no reports quantifying WUEg in maize hybrids released in different decades. In this study we quantify WUEg and its components (i.e. grain yield and seasonal ET) and we examine physiological traits during the critical period for kernel set (i.e. plant growth rate, PGRcp; ear growth rate, EGRcp; ET, ETcp and stomatal conductance), in an old and in two more recent maize hybrids grown under contrasting soil water availability. Three maize hybrids, DK2F10 (old hybrid released in 1980) and DK682RR and DK690MG (more recent hybrids, released in 2004), were grown in 5 experiments during 4 seasons; and irrigation and rainfed treatments were used to promote contrasting soil water availabilities. Soil water content was measured every 7–10 days with a neutron probe. Maximum WUEg tended to be higher for more recent (25.1 kg ha^{-1} mm^{-1}) than for the older hybrid (23.1 kg ha^{-1} mm^{-1}); and advantages of WUEg were larger and significantly higher in the more recent than in the older hybrid, at lower water availability. The greater WUEg of more recent hybrids was associated with greater grain yield at all water supplies; which was the result of a greater KNP. At low water availability, the greater KNP in more recent hybrids was related to greater PGRcp, ETcp and stomatal conductance than in the old maize hybrid.

1. Introduction

Water use efficiency for grain yield (WUEg) involves grain yield production and seasonal crop evapotranspiration (i.e. Grain yield/ET; Passioura, 1996). Understanding the associated physiological mechanisms contributing to its determination is required to better orientate breeding efforts, modeling and agronomic management towards greater yields stability under increasing climate variability (IPCC, 2014). It is known that the grain yield component of the WUEg has increased during the last decades for maize (*Zea mays* L.) hybrids (e.g. Echarte et al., 2000; Tollenaar and Lee, 2011). In Argentina, grain yield potential (i.e. when hybrids were grown in environments to which they are adapted and with no resource availability limitations) increased at a rate of 107 kg ha^{-1} yr^{-1} between 1965 and 2010 (Di Matteo et al., 2016). That increment was mainly attributed to a sharp rise in harvest index between 1982 and 1993 and to consistent increments in shoot biomass production (Echarte and Andrade, 2003; Luque et al., 2006; Echarte et al., 2013; Di Matteo et al., 2016). Higher grain yields under resource limited environments were also demonstrated in more recent than in older hybrids (e.g. Tollenaar and Wu, 1999). For example, more recent hybrids are more tolerant to low soil nitrogen availability (Rajcan and Tollenaar, 1999; Echarte et al., 2008), weed interference (Tollenaar et al., 1997) and high plant population density (Duvick and Cassman, 1999; Echarte et al., 2000; Tollenaar and Lee, 2002; Duvick et al., 2004). Moreover, tolerance to high plant density and stability across environments were closely associated in hybrids released in different decades (Di Matteo et al., 2016). Thus, the comparison between more recent and older maize hybrids has the potential to identify underlying processes influencing a greater grain yield under low water availability. Nevertheless, grain yield response to water deficiencies in particular, has been less studied in more recent than older hybrids. Retrospective studies focusing on water deficiency effects, have associated greater grain yield under low water availability with lower anthesis-silking interval and bareness reduction (e.g. Bolaños et al., 1993; Edmeades, 2013; Campos et al., 2006); however, in these studies, WUEg was not quantified.

The seasonal crop ET component of WUEg has remained similar among temperate maize hybrids released in different decades, under

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Table 1
Mean photosynthetically active radiation (PAR), mean air temperature, accumulated reference evapotranspiration (ET_0), and accumulated rainfall per month, in Experiments 1–5 and for a series of 30 years (H) at Balcarce, Argentina. Accumulated irrigation per month is depicted for the treatments: irrigated (I), rainfed from silking (Rs), rainfed during critical period for kernel set (Rc) and rainfed during grain filling (Rf), in Exp. 1–5.

	PAR (MJ m^{-2} d^{-1})					Mean air temperature (°C)					ET_0 (mm)					Rainfall (mm)					Irrigation (mm)								
Exp.	1	2	3	4-5	*H*	1	2	3	4-5	*H*	1	2	3	4-5	*H*	1	2	3	4-5	*H*	1		2			3	4		5
																					I	Rs	I	Rf	Rc	I	I	R	I
Oct	8,8	9,0	7,7	8,3	*8,0*	13,9	13,9	13,5	14,9	*13,6*	92	109	92	96	*88*	29	30	45	51	*86*									
Nov	10,7	10,2	10,1	10,8	*10,0*	19,8	17,2	16,3	17,8	*16,5*	136	132	120	137	*116*	53	70	116	64	*85*							51	16	27
Dic	11,6	10,9	12,5	11,2	*11,2*	20,7	19,2	20,9	20,2	*19,2*	162	151	175	165	*145*	31	121	33	239	*86*	121	121	21	21		153	134	11	53
Ene	12,3	11,1	11,4	10,3	*11,0*	22,5	22,9	22,3	21,1	*21,1*	188	170	159	143	*148*	25	84	185	152	*119*	72		140	36		51	53		22
Feb	10,2	9,7	10,2	10,6	*9,7*	22,2	20,4	20,1	21,1	*20,2*	138	114	116	133	*115*	64	108	33	33	*66*	24		159		159	58	144		133
Mar	7,2	6,8	8,2	7,7	*7,5*	20,5	18,5	19,9	16,4	*18,3*	105	86	111	90	*93*	66	203	22	114	*78*			64		64	19	17		8

low and under high water availability (Nagore et al., 2014; Reyes et al., 2015). In agreement, soil water content throughout the season was not different among tropical maize cultivars differing in cycle of selection (Bolaños et al., 1993). These results together, suggest greater WUEg in more recent than in older maize hybrids; and there is a lack of information regarding WUEg under contrasting soil water availability in hybrids released in different decades.

A greater WUEg of more recent maize hybrids is likely mediated by a greater kernel number set (e.g. Di Matteo et al., 2016). However, it is noteworthy that there are no previous studies focusing on the understanding of the mechanisms underlying kernel set determination together with crop ET, and under contrasting soil water availability in older and in more recent maize hybrids. Kernel number per plant (KNP) is associated with plant growth rate during the critical period for kernel set (PGRcp; Tollenaar and Daynard, 1978; Fischer and Palmer, 1984; Kiniry and Ritchie, 1985; Aluko and Fischer, 1988; Andrade et al., 1999). In maize, the KNP–PGRcp relationship has been described by two successive curves to account for the first and second ear in prolific plants, or a single curve in nonprolific plants (Tollenaar et al., 1992; Andrade et al., 1999; Vega et al., 2001; Echarte et al., 2004). The KNP-PGRcp relationship indicates a PGRcp threshold for kernel set at low PGRcp and a value of the asymptote at high PGRcp that represents the potential KNP (Tollenaar and Aguilera, 1992; Andrade et al., 1999; Vega et al., 2001; Echarte et al., 2004; Echarte and Tollenaar, 2006). A greater KNP at low and at high soil water availability could be associated with greater PGRcp and/or with greater KNP per unit PGRcp (KNP/PGRcp; Echarte and Tollenaar, 2006). Although seasonal ET was similar between older and more recent maize hybrids, daily ET during the critical period for kernel set (ETcp) was greater in more recent than older hybrids under low water availability (Nagore et al., 2014). Therefore, a greater PGRcp might contribute to a greater KNP in more recent than in older hybrids under low water availability. A greater KNP/PGRcp, by means of greater dry matter partitioning to the ear during the critical period for kernel set (i.e. greater ear growth rate, EGRcp), might also contribute to a greater KNP as suggested by Bolaños et al. (1993) and Reyes et al. (2015). In addition, a greater KNP/EGRcp might also influence a greater KNP/PGRcp in more recent than in the old hybrids.

We tested the hypothesis that WUEg is greater in more recent than in an old maize hybrid. The objectives of this study were to quantify WUEg and to examine physiological traits (i.e. PGRcp, EGRcp, stomatal conductance) and their association with ETcp and KNP, in an old and two more recent maize hybrids, under contrasting soil water availability. Results of this study will contribute to elucidate ecophysiological mechanisms associated with a greater WUEg in maize hybrids.

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 four seasons: 2008–2009 (Season 1, Exp. 1); 2009–2010 (Season 2, Exp. 2); 2010–2011 (Season 3, Exp. 3) and 2012–2013 (Season 4, Exps. 4 and 5). Soil was a silty clay loam soil (Typic Argiudoll; USDA Taxonomy) with a petrocalcic horizon between 140 cm and 160 cm depth, a clayey layer (Bt) between 40 cm and 90 cm depth, and with 5.4% top soil organic matter. Experiments were conducted under conventional tillage and crops were fertilized with 45 kg N ha^{-1} at sowing and with 150 kg N ha^{-1} at the V6 stage (Ritchie and Hanway, 1982). Sowing dates were October 23, 21, 20 and 25 during Seasons 1–4, respectively. The plots were over sown and thinned during V3 stage, to 7.5 pl m^{-2}, which is the recommended plant density for current hybrids in this area and it doesn‘t promote grain yield reductions in older hybrids (Echarte et al., 2000; Di Matteo et al., 2016). Weeds and insects were adequately controlled with mechanical and chemical methods. This area is characterized with