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Impact of high temperatures in maize: Phenology and yield components

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ABSTRACT

Heat stress is a main threat to current and future global maize production. Adaptation of maize to future warmer conditions requires improving our understanding of crop responses to elevated temperatures. For this purpose, the same short-season (FAO 300) maize hybrid PR37N01 was grown over three years of field experiments on three contrasting Spanish locations in terms of temperature regime. The information complemented three years of greenhouse experiments with the same hybrid, applying heat treatments at various critical moments of the crop cycle. Crop phenology, growth, grain yield, and yield components were monitored. An optimized beta function improved the calculation of thermal time compared to the linear-cutoff estimator with base and optimum temperatures of 8 and 34 °C, respectively. Our results showed that warmer temperatures accelerate development rate resulting in shorter vegetative and reproductive phases (*ca.* 30 days for the whole cycle). Heat stress did not cause silking delay in relation to anthesis (extended anthesis-silking interval), at least in the range of temperatures (maximum temperature up to 42.9 °C in the field and up to 52.5 °C in the greenhouse) considered in this study. Our results indicated that maize grain yield is reduced under heat stress mainly via pollen viability that in turn determines kernel number, although a smaller but significant effect of the female component has been also detected.

1. Introduction

FAO has reported an improvement in food security in the last two decades, with a global reduction of undernourished people of 216 million in 2015 compared to 1990–92. These figures are especially encouraging in developing regions dropping from 23.3% of the population undernourished in 1990–92 to 12.9% in 2015 (FAO et al., 2015). In spite of these positive data, the already observed and projected impacts of climate change on agriculture (IPCC, 2013) and their implications for the food security of current world population and of the 9 billion people foreseen by 2050 emphasize the urgent need for farmers to adapt to a changing climate (FAO, 2016). In addition, crops with high water requirements cultivated under semi-arid or arid conditions require to be adapted to the new climate conditions to increase water productivity and irrigation water efficiency (Molden et al., 2010) in an elevated temperature environment.

The major staple crops, such as maize (*Zea mays* L.), the cereal with greatest world production (in the period 2010–2014, average production was 932.7 Million Mg with an average yield of 5.27 Mg/ha, http://www.fao.org/faostat/en/) will need to adapt to the new conditions. Maize is cultivated in a wide range of climate conditions, following the rainy season in tropical regions and as a summer crop in temperate ones, with high irrigation requirements under semi-arid conditions. Maize adaptation should deal not only with changed climate averages, but also with the increased frequency and intensity of extreme events (IPCC, 2012). More specifically, several studies have identified heat stress as a main threat for future maize cultivation in several relevant production regions (e.g. Gourdji et al., 2013).

Kernel number, i.e. the size of the physiological sink of assimilates, is a key yield component to determine final maize grain yield (Fischer and Palmer, 1984; Andrade et al., 2000). In turn, this component is closely related to the source of assimilates during a narrow time window of four or five week period around anthesis (Fischer and Palmer, 1984; Otegui and Bonhomme, 1998; Andrade et al., 1999). No clear dependency of the kernel number on growth rates during the occurrence of heat stress in pre-silking period has been found (Cicchino

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et al., 2010b). However, heat stress during the period around silking leads to high yield reduction (Cicchino et al., 2010b) affecting both plant sources and sinks. Source capacity is directly affected by a reduced synthesis of carbohydrates (Barnabás et al., 2008), in turn caused by decreased photosynthesis and escalated respiration rates (Rattalino-Edreira and Otegui, 2012; Wahid et al., 2007; Ordóñez et al., 2015). Sink capacity is affected by the disruption of the anthesis-silking synchrony, reduced ovule fertilization and increased kernel abortion. In turn, these effects disturbs pollination and kernel set and can result in severe yield losses (Herrero and Johnson, 1980; Rattalino-Edreira et al., 2011; Ordóñez et al., 2015; Dupuis and Dumas, 1990; Cicchino et al., 2010b). Also, recent studies (Rattalino-Edreira et al., 2011; Ordóñez et al., 2015) have found an important role of the female component of the sinks in the maize response to heat stress.

The upper optimum temperature for maize flowering has been considered to be between 29 and 37.3 °C (Schlenker and Roberts, 2009; Gilmore and Rogers, 1958; Tollenaar et al., 1979; Cicchino et al., 2010b; Porter and Semenov, 2005; Sánchez et al., 2014). Some authors have explained partially this wide range by the experimental error coming from considering air temperature instead of canopy temperature (Craufurd et al., 2013; Siebert et al., 2014, 2017; Webber et al., 2016; Lobell et al., 2008) or plant profile temperature (Rattalino-Edreira and Otegui, 2012). Differences in vapor pressure deficit (VPD) may also affect these responses. On one hand, the difference between those temperatures can be especially large under irrigated conditions (up to 10 °C according to Kimball et al., 2015), but even the smaller differences registered under rainfed conditions (*ca.* 2 °C) can lead to underestimation of heat stress impact (Webber et al., 2016). Most of the previous experiments introduced modifications in temperature, gas exchange, wind profile and radiation not just in the greenhouse experiments but also in the field ones (e.g. by using polyethylene films as Cicchino et al., 2010a,b; Rattalino-Edreira et al., 2011; Ordóñez et al., 2015) to achieve fully or partially controlled heat stress conditions. On the other hand, increases in air temperature under field conditions usually induce higher VPD, enhancing the demand for soil water and the effect of water deficits (Mittler, 2006), which in turn can raise canopy temperature.

The objective of this study was to improve the understanding of the response of maize development, growth and grain production to heat stress conditions. For that reason, our study combines data collection under controlled conditions (greenhouse) with field experiments under natural conditions with unperturbed wind, radiation, humidity, and temperature regimes. Also, data collection on the same hybrid under several field and controlled conditions across all years was crucial to remove the uncertainty linked to genotype variation.

2. Materials and methods

2.1. Experimental conditions and design

2.1.1. Field treatments

The study was conducted over three years (2014–2016) growing the short-season maize (*Zea mays* L.) hybrid PR37N01 (FAO-300) in three locations in Spain with a North-South thermal gradient (Candás in Northern Spain, Aranjuez a Central site, and Córdoba in the South, Fig. 1a). The soils of the field experiments (Fig. 1b), were fertilized according to soil analysis recommendations, typically with 250 kg N/ha split in two applications at V4 and V8, to avoid nutrient limitation. Irrigation was applied weekly or as required to maintain soil moisture near field capacity. The amounts varied according to the soil, year, and crop cycle based on the reference evapotranspiration (ET0), but typically 40 mm were applied weekly for a total seasonal irrigation of ca. 550–700 mm in the Center and South, less in the North. Crops were protected from pests, diseases and weeds, and management was adjusted to local conditions and practices.

Treatments for field experiments consisted of two sowing dates in each location (Table 1), aimed to cover a wide range of temperatures through the growing cycle. The experimental design was completely randomized, with four replications of plots 10–12 m length containing six rows 0.75 m apart, at a target plant population density of 5 plants m^{-2}.

2.1.2. Greenhouse treatments

In parallel, a greenhouse experiment was conducted over the same years and with the same hybrid in Madrid (within the Experimental Fields of the Technical University of Madrid, 40°26'14″N 3°44'1″W, 657 m above mean sea level). Two greenhouses, cool and hot, differing in target daytime temperature, provided the controlled environment to complement the information for this work. The controls were adjusted in the cool greenhouse to maintain the daytime temperature around 25° C, and above 35° C in the hot greenhouse. Late in the afternoon, heating and cooling systems were switched off and windows opened allowing both greenhouses to equilibrate with outside temperatures. Sensors measuring photosynthetically active radiation, PAR (QSO-S, Decagon, Pullman, Washington, USA) and temperature and relative humidity (PASS VP-3, Decagon, Pullman, Washington, USA) were located in the center of each greenhouse. The same hybrid used in the field experiments was sown in 15-L pots filled each year with a fresh mixture (1:1:1) of sand, peat, and compost. Three seeds per pot were planted on late May or early June during 2014, 2015, and 2016, and thinned to one plant at V3. Pots were irrigated twice a day, 8:30 am and 8:30 pm, during 2 min, and fertilized weekly with 5 g per pot of 15-15-15/18 (water soluble SO_3). The experimental unit consisted of three plants replicated three times, with two pollen sources used for pollination, for a total of 18 plants per treatment. All topmost ears were hand-pollinated at mid-morning three days after silking, half with pollen from the same treatment (local pollen) and half with fresh pollen collected in a nearby field. Heat treatments consisted of moving 18 plants of the corresponding treatment from the cool greenhouse to the hot greenhouse, and returning the plants back to the cool greenhouse seven days later. Heat treatments were applied at specific phenological times (Table 1). In 2015 and 2016 an additional treatment was incorporated by maintaining 18 plants in the hot greenhouse all the season. In 2016 the V4 treatment was changed. Two complete treatments were maintained in the hot and in the cool greenhouses until V4 and then the plants were switched reciprocally and maintained in the new location until the end of the season. Also in 2016, to further examine heat effect on pollen and pistils, we incorporated two additional treatments with plants growing all season in the hot and cool greenhouses. Half of the plants growing in the cool greenhouse were pollinated with pollen from plants growing in the hot greenhouse. Reciprocally, half of the plants growing in the hot greenhouse, were pollinated with pollen from the cool greenhouse. The remaining plants as usual, were pollinated with fresh pollen. No grain filling (GF) treatment was included in 2016. Therefore, there were six treatments in 2014 (108 plants from 18 plants x six treatments), seven in 2015 and nine in 2016. Treatments were identified as follows: plants in the cool greenhouse all crop cycle or control (C), heat at V4 (V4), in cool greenhouse up to V4, then moved to hot greenhouse (V4c), in hot greenhouse up to V4, then moved to the cool greenhouse (V4 h), heat at V9 (V9), heat at anthesis (FL), heat at lag phase (LG), heat at early GF, heat all crop cycle (H), plants in the cool greenhouse pollinated with pollen from the hot greenhouse (CxH), and the corresponding opposite (HxC).

2.2. Weather data

In the field experiments, automatic weather stations at each site provided daily records of maximum and minimum temperature, precipitation and radiation for all sites, and also relative humidity and wind speed for the Central and South sites. Weather station in Cordoba is part of the Agroclimatic Information Network (RIA, in Spanish) described in Gavilán et al. (2006).