Field Crops Research 156 (2014) 123–134

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Phosphorus acquisition and internal utilization efficiency among maize landraces from the central Mexican highlands

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ARTICLE INFO

Article history:
Received 11 May 2013
Received in revised form 5 November 2013
Accepted 9 November 2013

Keywords:
Zea mays L.
Acid soil
P acquisition efficiency
P utilization efficiency

ABSTRACT

In many low input maize production systems phosphorus (P) is in limited supply. Improved crops that acquire and use P more efficiently are a sustainable solution to increase crop yield in these systems. This study determined the contribution of P acquisition efficiency (PAE) and P utilization efficiency (PUTE) in determining P use efficiency (PUE) of 20 maize accessions from the Purhepecha Plateau, Michoacan, grown on a P-deficient Andisol, at two locations with low (23 kg P_2O_5 ha^{-1}) and high (97 kg P_2O_5 ha^{-1}) P fertilization under rain-fed conditions. Under P deficiency conditions in the acid soil, both PAE and PUTE were important factors explaining the variation in P use efficiency at both P levels. Greater P use efficiency was related to an improved distribution of dry matter in the plants and a lower absorbed P allocated in the grain. Low grain P concentrations at maturity were not associated with reductions in grain yield, nor were they significantly correlated to HI, suggesting that exploiting genotypic variation for this trait may be productive. The study identified genetic variation among maize landraces in their response of PUTE. On a P-deficient acidic soil, accessions CB-2, DP × Tromba, HV313 × DEM, Macho III-04, and CIMMYT-1, were categorized as the most P efficient and the most responsive to increased P availability. In contrast, late maturing P-efficient accessions SHUI-2, CB-2, AS-4, and ZR-6 showed the greatest variation for P uptake under low P conditions. Late maturity improved growth and yield in low P soils. These accessions expressed the desired traits for PUE, which may be exploited in breeding efforts.

1. Introduction

Phosphorus (P) deficiency is considered a major factor limiting crop productivity, especially among soils in the tropics and subtropics. Compared to other major nutrients, P is by far the least mobile and least available to plants under soil conditions (Hinsinger, 2001). Acid andisols contain considerable amounts of P, but a large proportion is bound to different soil constituents that form complexes of limited bioavailability (Driessen et al., 2001). This type of soil is commonly referred to as a 'P-fixing' soil and the concentration of available P (phosphate) in solution is suboptimal for crop production. An initial strategy for soils with low total P content is regular amendment with small doses of P fertilizer. However, in soils with high total P content in which most of the P is fixed, fertilizer P will also be fixed. In this soil type, plants respond to P fertilizer application but annual P applications are needed to sustain crop yields (Ramaekers et al., 2010). Another approach is to enhance the plant's efficiency to acquire and utilize soil P (Shenoy and Kalagudi, 2005).

Improving the P use efficiency (PUE) for crop growth requires enhanced P acquisition efficiency (PAE) by plants from the soil and enhanced utilization of P in processes that lead to faster growth and greater allocation of biomass to the harvestable plant components (PUTE) (Veneklaas et al., 2012). The main mechanisms related to increased PAE include more favorable root architecture and morphology, mycorrhizal associations, enhanced expression of high affinity transporters, rhizosphere alteration, and secretion of organic compounds into the rhizosphere such as phosphatases and organic acids (Ramaekers et al., 2010; Richardson et al., 2011). A higher PUTE can be achieved by plants that have lower net P concentrations as well as by optimal distribution and redistribution of P in the plant allowing maximum growth and increased biomass allocated to harvestable yield (Wang et al., 2010). Improvements in P distribution within the plant may be achieved by increased remobilization from senescing tissue as well as reduced partitioning of P to developing grains (Veneklaas et al., 2012).

The concepts of nutrient acquisition efficiency, in the sense of nutrients acquired from the soil and/or fertilizer, and internal nutrient utilization efficiency (defined as plant yield per unit of nutrient in the plant) have been considered the two major components of

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http://dx.doi.org/10.1016/j.fcr.2013.11.005

plant nutrient use efficiency, in situations of low or high nutrient supply (Moll et al., 1982). However, other nutrient efficiency classification systems take into account plant performance both in the presence and absent of nutrient stress. For example, Gerloff (1977) separated cultivars as P efficient (higher yielding than other cultivars under low P supply) and/or P responsive (higher yielding than other cultivars under high P supply). This classification groups cultivars based on performance under low (efficient vs. inefficient) and high (responders vs. non-responders) nutrient supply, and permits identification of cultivars with adaptations to a range of soil nutrient conditions.

Current breeding strategies seek to select for P responsiveness (Wissuwa et al., 2009). However, there have been a few successful examples of improving PUE (Shenoy and Kalagudi, 2005; Wissuwa et al., 2009; Wang et al., 2010). PUE is the ability of crop genotypes to yield under low available-P concentrations. To increase PUE, component traits such as PAE (absorption/uptake), translocation (transport/partitioning/remobilization) and PUTE must be improved (Good et al., 2004). Inter- and intra-specific variability for these traits is under both genetic and physiological control, and is modified by plant-environmental interactions (Shenoy and Kalagudi, 2005). In order to improve PUE in crops, it is important to explore genetic variation for all the associated traits.

Genotypic variation in PUE has been identified for a number of cereal crops including: maize [*Zea mays* L. (Fageria and Baligar, 1997a)], rice [*Oryza sativa* L. (Fageria and Baligar, 1997b; Wissuwa and Ae, 2001)], wheat [*Triticum aestivum* L. (Manske et al., 2000)] and barley [*Hordeum vulgare* L. (Osborne and Rengel, 2002)]. The relative importance of PAE and PUTE over PUE varies among crops. Greater significance of PUTE than PAE has been reported in maize (Corrales et al., 2007) and potato [*Solanum tuberosum* L. (Balemi and Schenk, 2009)]. The greatest significance of PAE has been identified in common bean [*Phaseolus vulgaris* L. (Beebe et al., 2006)], wheat [*T. aestivum* L. (Manske et al., 2001; Osborne and Rengel, 2002)], barley [*H. vulgare* L. (Ozturk et al., 2005)], rice [*O. sativa* L. (Wissuwa and Ae, 2001)], and maize [*Z. mays* L.] (Parentoni and Lopes de Souza, 2008).

Genotypic variation in nutrient use efficiency has also been identified in cereal landraces, which have developed mostly in environments with low nutrient availability and may therefore represent a source of variation for development of varieties adapted to low fertilizer input cropping systems (Newton et al., 2010). For instance, late-maturing source populations from tropical maize landraces that exhibit high net N uptake, partition a large proportion of dry matter and N to the grain, and/or maintain high grain N concentrations, may serve as components for traits with adaptive value for N-limited environments (Lafitte et al., 1997). Selected wheat landraces with well-developed root systems may be used as a source of variation for the genetic improvement of nutrient uptake in high yielding elite germplasm (Waines and Ehdaie, 2007) and soil exploration by roots has been shown to be essential for absorption of both P (Gahoonia and Nielsen, 2004) and N (Wiesler and Horst, 1994).

The Mexican highlands, including the Purhepecha region of Michoacan, Mexico, with preferential use of traditional maize varieties among farmers, are an important repository of genetic resources (Mijangos-Cortés et al., 2007). P efficient maize landraces can be of benefit in improving the use of native soil P and residues of P applied as fertilizer on both low P soils and on soils adequately supplied with P (Bayuelo-Jiménez et al., 2011). Field studies confirmed that the available maize accessions differ considerably in root traits, suggesting that indirect selection for P efficiency has occurred (Bayuelo-Jiménez et al., 2011).

The objectives of this study were to evaluate the contribution of PAE and PUTE and traits related to PUE of maize landraces in a P-deficient Andisol, and classify the landraces on the basis of their performance (yield) under low (efficient vs. inefficient) and high (responsive vs. non-responsive) P supply.

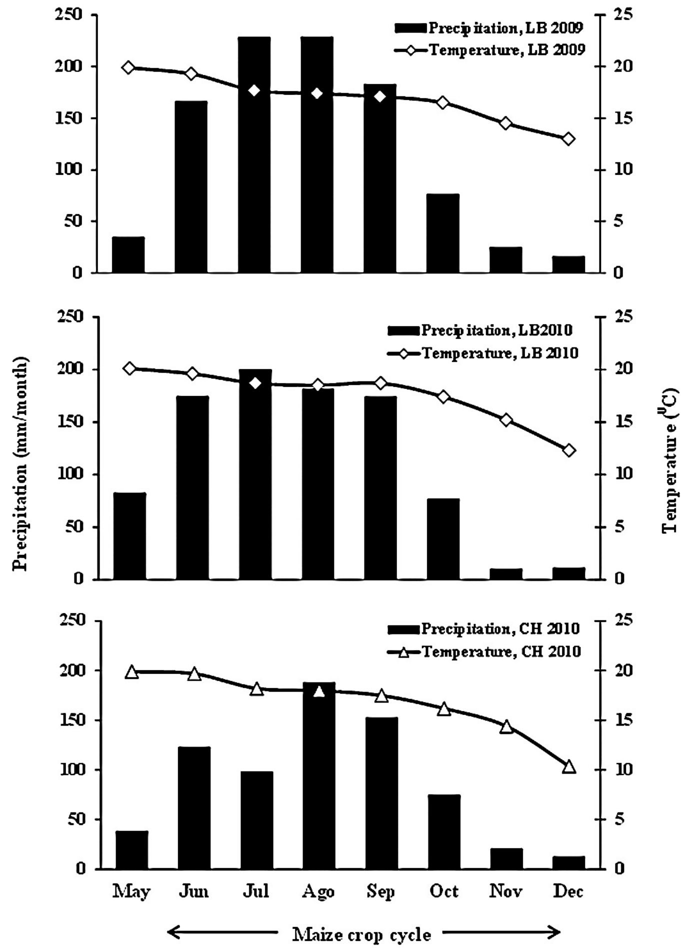

Fig. 1. Monthly mean precipitation and temperature in Bonilla (LB) and Charahuen (CH), averages measured during experiments 1 and 2 in Bonilla (2009, 2010) and experiment 3 in Charahuen (2010).

2. Materials and methods

2.1. Experimental site

The study sites are located in the Purhepecha Plateau in the Trans Mexican Volcanic Belt, on the center area of the State of Michoacan (between 19°15′ and 20°00′ North; 101°28′ and 102°30′ West). The topography of this region is heterogeneous, forming a diversity of microclimatic sites. Altitudes vary from 1000 to 2800 m and the region is characterized by a temperate sub humid climate with summer rains providing 600 to 1200 mm annually, mild temperatures and high relative humidity (Alcalá de Jesús et al., 2001).

Three field trials used 20 maize accessions with low and high P fertilization under rain-fed conditions, in farmer's fields in the central highlands of Michoacan, Mexico during the growing seasons of 2009 and 2010. Trials 1 (2009) and 2 (2010) were sited in Bonilla and Trial 3 (2010) in Charahuen (Table 1). Bonilla is located at 19°24′N, 101°39′W, 2400 masl. Charahuen is located 19°52′N, 101°70′W, 2062 masl. The annual mean temperature was 13 to 20 °C with a mean monthly maximum of 20 °C in May and a minimum of 12 °C in December (data available from 1988 to 2010 from an adjacent weather station). The temperature in the summer was mild due to the high altitude, and declined near the end of the crop cycle. Precipitation occurs mainly between June and September (Fig. 1).