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Additive yield response of chickpea (*Cicer arietinum* L.) to rhizobium inoculation and phosphorus fertilizer across smallholder farms in Ethiopia

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ABSTRACT

The impacts of rhizobium inoculation on growth and yield of chickpea have mainly been tested in experiments conducted in greenhouses or on research stations. We report the response of the crop to inoculation (I) and phosphorus fertilizer (P) application across a large number of smallholder's farms over four regions of Ethiopia, covering diverse soil fertility and agro-ecological conditions. Increased grain yields due to the soil fertility treatments was evident for 99% target farmers. On average, I and P increased grain yield by 21% and 25% respectively, while the combined application of I and P resulted in a 38% increase. However, observed grain yields on control plots and responses to the treatments on individual farms varied greatly, and relative yield responses (%; yield of P and/I minus control yield, divided by control yield) ranged from 3% to 138%. With the exception of a few extremely poorly yielding locations, average responses to P and I were high across a wide range of control yields, indicating the possibility of boosting chickpea productivity for smallholders with P fertilizer and inoculant technology. Variation in response to rhizobium inoculation was mostly independent of agro-ecology and soil type although it was found to be low on a number of farms with extremely high N contents (%). Assuming that a relative yield increase of 10% due to treatment effects is required to be visible, 71%, 73% and 92% of the farmers observed a yield benefit by applying P, I, and P + I, respectively. The results are discussed with respect to the additive benefits of P fertilizers and rhizobial inoculation and their implications for wide scale promotion of inoculant technology to smallholders.

1. Introduction

Chickpea (*Cicer arietinum* L.) is globally the third most important food legume after common bean and soybean (Namvar and Sharifi, 2011). It is widely cultivated by smallholders in Mediterranean and semi-arid climates but in Africa is largely restricted to the cool highlands of Ethiopia (Anbessa and Bejiga, 2002). However, it also grows in Sudan under irrigation and rain-fed systems and is an increasingly important crop in Tanzania. In 2014, Ethiopia produced almost 60% of Africa's total chickpea (FAOSTAT, 2014; Ojiewo, 2016). The total area of chickpea in Ethiopia has increased from 168,000–230,000 ha over the past decade (CSA, 2014), with desi varieties grown mainly for the local market and the larger seeded, Kabuli varieties largely for export. Yet productivity of chickpea remains low, with national average yield of 1.7 $t\,ha^{-1}$ (BTL, 2013; FAOSTAT, 2014; CSA, 2016, 2017), far below the potential yield of 4–5 $t\,ha^{-1}$ reported on experimental stations (Bejiga and van der Maesen, 2006; Fikre, 2016).

Chickpea occupies an important position amongst the pulse crops grown in Ethiopia because of its multiple functions. It is a key component of the daily diet, and thus an important protein source for Ethiopian households who cannot afford animal products. Chickpea residue, locally known as "Defeka", is important as a feed resource for livestock during the dry months of the year when green fodder is unavailable. This helps farmers to keep robust oxen whose draught power is critical for land preparation at the onset of the rains. Chickpea plays an important role in Ethiopia's foreign exchange earnings through

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export to Asia and Europe (Shiferaw and Teklewold, 2007). Another attractive feature of chickpea is its ability to fix atmospheric nitrogen in symbiosis with rhizobia, contributing directly to grain protein and reducing the need for N fertilizer for subsequent crops. It thereby has great potential to improve soil N status (Tena et al., 2016; Ben Romdhane et al., 2008; Funga et al., 2016; Khaitov et al., 2016) and is an ideal candidate for intensification of the tef monoculture that is common in Ethiopia. Chickpea is produced mainly in the central, northern and north western highland areas at elevations of 1400–2400 m above sea level where annual rainfall ranges from 700 and 2000 mm. It is often grown after the cereals wheat (*Triticum* spp.) and tef (*Eragrostis tef* (Zucc.) Trotter) are harvested on vertisols using residual moisture which extends the cropping season through September–December. As a result, growing chickpea allows the farmers to produce extra crop on the same land.

Legume yields and nitrogen fixation depends on the genotype of the legume (G_L), the rhizobium strain (G_R) and the interactions of these with the bio-physical environment (E), and management practices (M) expressed as the interaction: $(G_L \times G_R) \times E \times M$ (Giller et al., 2013). Research efforts have focused on breeding (MoARD, 2009; Jarso et al., 2011; BTL, 2013). The use of agrochemical inputs with legumes remains limited in Africa (Chianu et al., 2011), and chickpea is grown without fertilizer often on marginal lands in Ethiopia, with a common notion among farmers that legume crops do not need nutrient inputs. Yet poor legume yields are often a reflection of poor soil fertility (Franke et al., 2016).

Chickpea can fix 60–80% of its nitrogen requirement (SPG, 2016; Giller, 2001), amounting to 60–176 kg N ha^{-1} (Beck et al., 1991; Shiferaw et al., 2004). It is selective in its symbiotic requirement, nodulating with only a specific group of rhizobium species (Tena et al., 2016; SPG, 2016). The absence of compatible strains and the small rhizobial population in the soil are important limitations for nodule formation in chickpea (Kantar et al., 2010). Inoculation with effective strains at planting time is recommended if the soil population density of compatible rhizobia is less than 50 cells per gram of soil (Thies et al., 1991a,b). There is increasing evidence to suggest that inoculation enhances plant growth, grain and biomass yield in chickpea (Ben Romdhane et al., 2008; Funga et al., 2016; Khaitov et al., 2016; Tena et al., 2016). In Ethiopia, experiments to date examining the effect of rhizobium inoculation on chickpea growth and yields have been largely restricted to greenhouses and research stations. Here, we report the responses of chickpea to inoculation (I) and phosphorus fertilizer (P) application from widespread testing on smallholder farmers' fields. Our central aim was to understand the effect of the treatments (I, P and/or I + P) on grain yields of the crop across a large number of smallholders' plots representing diverse soil fertility and agro-ecological conditions. To this end we conducted simple trials on more than 100 farmers' fields in four Woredas (districts) in central, south and south-east Ethiopia. In addition, the variation in response to the soil fertility treatments across individual farms were explored to identify whether we could identify variables that explain the occurrence and magnitude of response. Such knowledge is important to assist both in targeting of the technologies and to identify the need for further research on rehabilitation measures.

2. Materials and methods

2.1. The test environment

On-farm demonstration trials were conducted over four cropping seasons from 2012 to 2015, in four different Woredas (districts), namely Ada'a/Gimbichu (Central), Damote-Gale (South), and Ginir (South-east Ethiopia) (Fig. 1). The sites are located within an elevational range of 1860–2493 m above sea level, with annual mean temperature range of 18–19.5 °C, and annual mean rainfall of 815–1255 mm (Table 1). There was a significant drought in 2015 which was an El Niño year. The climates at Ada'a/Gimbichu and Giner are characterized as "hot to warm sub humid" while Damote-Gale is "Hot to warm moist". T'eff (*Eragrostis tef* (Zucc.) Trotter), wheat (*Triticum* spp.) and maize (*Zea mays* L.) are the most important cereal crops, but the crop mix varies among locations with more diversity at Damote-Gale (Table 1). All Woredas have a mixed farming system with crops and livestock. In all cases, chickpea is grown on residual moisture immediately following the main crop harvest – wheat (Ginir), teff (Ada'a/Gimbichu) and maize and/or tubers and spices (Damote-Gale). The soils of the trial sites are Eutric Vertisols at Ada'a/Gimbichu and Giner while Humic Nitisols are dominant at Damote-Gale (Table 1).

2.2. On-farm demonstration trials

In 2012 and 2013, 23 farmers participated in on-farm demonstration trials. In the 2014 and 2015 seasons, the number of farmers participating increased to 93. The demonstration trials served for learning about improved chickpea technology packages through farmers' field days, visits and technology evaluation events organized for large number of farmers from adjoining Kebeles (villages). Plots were selected to be accessible for farmers and visible to passers-by. The trials were not replicated on each farm, but farms were considered as replicates (Table 2).

Trials included four treatments; an uninoculated and unfertilized control plot (C), a plot inoculated with rhizobium (I), inoculated but with phosphorus fertilizer (P), and both rhizobium inoculated and phosphorus fertilized (P + I). Due to lack of availability, the phosphorus fertilizers sources differ over the seasons, and were TSP (tri-super phosphate) in 2012, DAP (di-ammonium phosphate) in 2013–2014 and an NPS blend in 2015. The rate was held constant at 23 P_2O_5 kg ha^{-1} (13 kg P ha^{-1}) applied at sowing. Altogether, three improved chickpea varieties (two Kabuli type – Arerti and Habru and one Desi type – Natoli) were selected on the basis of local adaptation and market preferences (Table 2). Natoli and Habru are short to medium maturity (88–150 days) while the Arerti has relatively long duration (105–155 days). Seed was sown in rows 30–40 cm apart, spaced 10 cm within rows. Each treatment plot measured 10 m by 10 m with 1 m paths separating the plots.

Inoculants were purchased from the sole commercial inoculant producer in Ethiopia: Menagesha Biotech Industry PLC, Addis Ababa. The inoculants used lignite as a carrier and two chickpea *Mesorhizobium* strains (CP-41 in 2012 and CP-029 in 2013–2015). These strains have been tested under a wide range of ecological conditions in Ethiopia (Tena et al., 2016; Funga et al., 2016). Seeds were inoculated at a rate of 5 g of inoculant per kg of seed using sugar solution as a sticker. Inoculation was done under shade and the inoculated seed was kept for few minutes until air dry before planting. In all farms, uninoculated treatments plots were sown first to avoid cross contamination.

Composite soil samples were collected before planting at depth of 0–20 cm sampled at 13 even intervals in a "W" pattern throughout the field. The samples were weighed, air-dried, ground to pass through a 2 mm sieve before analysis. Soils were analysed following standard laboratory procedures in soil laboratories in Ethiopia (2012–2014) and at IITA at Ibadan, Nigeria (2015) for pH (1:1 soil to H_2O), organic C (Walkley–Black), total N (Kjeldahl), P Mehlich, and exchangeable K, Ca and Mg according to standard procedures (IITA, 1982). The composite soil sample from each field at Damote-Gale was used to determine the population of rhizobia compatible to chickpea following most-probable-number (MPN) plant infection count (Somasegaran and Hoben, 1994) during the 2012 crop season.

Plots were sown between mid-August and late-September and managed by the farmers assisted by a development agent (DA) or field technician, who were responsible for keeping records of different operations. Nodulation was assessed at mid flowering growth stage at Damote (in 2012 and 2014) from randomly sampled ten plants in the plot at each of the respective treatments. The plants were uprooted carefully, washed and the number of nodules recorded. At the end of