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Characterization of the main chickpea cropping systems in India using a yield gap analysis approach

Amir Hajjarpoor[a], Vincent Vadez[b], Afshin Soltani[a], Pooran Gaur[b], Anthony Whitbread[b], Dharani Suresh Babu[b], Murali Krishna Gumma[b], Madina Diancoumba[c], Jana Kholová[b,*]

[a] Agronomy Group, Gorgan University of Agricultural Sciences and Natural Resources, Gorgan 49138-15739, Iran
[b] International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Hyderabad 502324, Andhra Pradesh, India
[c] International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), BP 320 Bamako, Mali

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ABSTRACT

Chickpea is an important livelihood option and nutritious food source for many subsistence farming communities in the developing world. Although India is the biggest chickpea producing nation, the demands of its growing population are not met by domestic production. This study uses a modelling approach to quantify the region-specific constraints and yield gaps limiting chickpea productivity and evaluates the potential for boosting production in the major chickpea growing regions of India. Information on bio-geo-physical properties (weather, soil, crop, management) of these regions was collated and the SSM-iLegume model used to reproduce seasonal variability and potential yield for the major chickpea producing districts to estimate the yield gap. Further, we estimated the difference between the yield potential and the currently achieved yields; i.e. yield-gap. The results showed that India has the capacity to produce 40% more chickpea (i.e. 80% of the achievable yield) than is the current production status under the standard crop management practices. We also found that chickpea crop production in rain-fed systems is largely limited by water availability during the season (~64%) but with large variability in the drought stress effect on yields between the investigated districts. Observed geo-bio-physical properties of the districts and simulation results of yield gap analysis were used to cluster chickpea-growing districts into six distinct units with higher degrees of similarities; i.e. homogeneous system units (HSU). Within each HSU a similar system response to genotype-by-management (GxM) intervention is expected and the effects of particular interventions could be further tested using the modelling set-up developed for this study. The identified HSUs, each with a well-defined set of yield-limiting constraints, are proposed as authentic breeding units in crop improvement programs ("target population of environments") and we further discuss the need to use the HSU-specific breeding strategy to enhance chickpea production in India.

1. Introduction

Due to increasing concerns about the future food and nutrition security, maximizing crop production remains an important agricultural research target (Foley et al., 2011). The uncertainty that climate change brings is a major concern for the agricultural systems already burdened by adverse climates and many yield limiting factors – e.g. the semi-arid tropical (SAT) cropping systems.

One of the sensible approaches to dealing with these uncertainties is to analyze the major constraints of a given cropping system and design the appropriate interventions to lift up the current yields closer to their achievable potential, e.g. through introduction of adapted cultivars or more suitable crop management practices (Soltani et al., 2016; Pradhan et al., 2015; Chauhan and Rachaputi, 2014). Although testing the genotype, environment, and management interactions (GxExM) experimentally in the field ultimately reflects the ground reality, this approach is usually very limited by the number of seasons, sites, cultivars and management combinations which can be realistically evaluated. By contrast, cropping system productivity under dynamic GxExM scenarios can be reasonably well captured using system-crop modelling tools (Hall and Richards, 2013; Grassini et al., 2015). Cropping systems analysis using mechanistic models allows the estimation of production potential, understand system limits and define the most suitable system interventions which will result in productivity improvements by testing GxExM combinations in-silico (van Ittersum et al., 2013; Anderson et al., 2016).

Yield gap analysis is a methodology which has been developed to navigate and understand system constraints and to explore ways to

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* Corresponding author.
E-mail address: j.kholova@cgiar.org (J. Kholová).

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increase crop production (Hoffmann et al., 2015, 2017; van Ittersum et al., 2013). A yield gap is the difference (gap) between yield currently achieved on farms and the yield that can be achieved by using the best agronomy practices on-station (in-vivo) or simulated (in-silico) (van Ittersum et al., 2013; Lobell et al., 2009).

Crop models have been shown to be a relevant method to estimate yield potential under rain-fed and irrigated conditions as crop models can account for variation in weather, soil, crop and management and their interactions (Lobell et al., 2009; van Ittersum et al., 2013; Holzworth et al., 2014; Anderson et al., 2016). In-silico scenario analysis can further help us to design strategies with the highest probability to increase the yield per unit of land (i.e sustainable intensification), especially for countries like India where expansion of agricultural lands is limited (Alexandratos and Bruinsma, 2012). Sustainable intensification may also reduce the rate of agricultural land exploitation in other cases (van Wart et al., 2013; Bommarco et al., 2013; Foley et al., 2011).

Crop simulations have been used to classify the crop production regions into a “target populations of environment” suggested by Cooper et al. (1997), Chapman et al. (2000), Chenu et al. (2011), i.e. homogeneous system units with high degree of environment-management-socioeconomic similarities which allow designing a unique crop-management intervention (Chauhan and Rachaputi, 2014). To date, yield gap studies largely focus on cereals, especially wheat, maize and rice which account for a major part of the human staple diet (e.g. Hochman et al., 2013; Meng et al., 2013; Lu and Fan, 2013; Schulthess et al., 2013; Tanaka et al., 2013; Tanaka et al., 2015; Deihimfard et al., 2015; Liu et al., 2016; Xu et al., 2016).

The sole fact that the yields and production of pulses crops have been stagnant, especially in semi-arid tropics (SAT; Nedumaran et al., 2013), calls for more research on legume cropping systems. The limited yield gap analyses which have been conducted for various pulse crops in India (Bhatia et al., 2006, 2008) all indicate huge opportunities to increase production in these systems. It is, therefore, surprising, that a rigorous study has not been conducted for chickpea in India, despite India being the largest global producer of pulses (~30% share) and consumer of pulses (Nedumaran et al., 2013), with an imperative to reduce expensive pulse imports (Ali and Gupta, 2012; FAO, 2016, Anderson et al., 2016). This situation implies that previous system interventions have not resolved the region-specific production constraints and calls for more appropriate systems interventions for the complex SAT agro-ecologies (e.g. Pradhan et al., 2015; Mace and Jordan, 2011; Vadez et al., 2013, Kholová et al., 2014; Chauhan and Rachaputi, 2014).

Therefore, the main objectives of this study were to i) to identify the main chickpea production systems in India and use the crop modelling to estimate productivity, ii) characterize and understand the main production systems limitations using a yield gap analysis approach, iii) define homogeneous chickpea system units using the geo-bio-physical and model-outputs indicators generated in i) and ii); and iv) based on the findings, lay the ground for further analysis of region-specific constraints and interventions to increase production in these systems.

2. Materials and methods

The main aim of this study was to collect relevant data and develop sound methodology to segregate the major chickpea production tract in India into the geo-bio-physically distinct units with high degree of similarities which could be further considered as authentic units in support of breeding programs (“target population of environments”, TPEs). To achieve this, we gathered district-wise time-series data of chickpea area (ha), production (kg) and productivity (kg ha^{-1}). Based on this information, we defined the major chickpea production tract as districts encompassing 75% of the total area sown to chickpea. We also gathered information about common field management practices, cultivar main characteristics and soil information relevant for each district. To compensate for erratic coverage and low quality of observed weather information across our focus area, we chose to evaluate and use a synthetic weather data as a substitutes. This information was further used to simulate the chickpea yields and compare with observed records (yield gap analysis). All observed and simulated geo-bio-physical properties of the districts within the major production region were finally used to sensibly separate the district into clusters with similar degrees of homogeneity (“homogeneous chickpea system units”) which are proposed as authentic breeding units to support the crop improvement programs (“target population of environments”).

2.1. Definition of target chickpea production systems

To define the main chickpea production tract in India we gathered a time-series (1996–2010) of district-level area (ha/district), production (kg/district), yield (kg ha^{-1}) and information on proportion and mode of irrigated area in ~280 districts in India (Ministry of Agriculture and Farmers Welfare, Govt. of India). The time-series (1996–2010) chosen, represents the period where records were available for all districts and were considered to capture the seasonal variability in yields of the recent locally preferred cultivars. Consequently, we sorted the districts according to the average area under chickpea cultivations and selected the districts where at least 75% of the total area was under chickpea cultivation (the district minimum average production area was 45,000 ha in the latest 15 years). This exercise defined the area of our interest; i.e. major chickpea production tract in India (Fig. 1). To create a continuous geographical unit we also included few of the adjacent districts (i.e. 29 adjacent districts) therefore our analyses finally encompassed 78 districts covering 82% of total chickpea cropping area between the base periods (1996–2010).

2.2. Environment (Soil and weather data)

Soil data were compiled from the National Bureau of Soil Survey and Land Use Planning (NBSS & LUP) in Bangalore, the International Soil Reference and Information Centre (ISRIC) and the main soils overview could be found at http://droppr.org/data/map/hc27. In the main chickpea production tract in India, as defined above, there were five most prevalent soil types with different effective soil depth and these were chosen to represent the region. At the whole India scale, we assumed these five dominant soil types sensibly represented the soil heterogeneity across major chickpea tract and so these were allotted to each simulation unit; Chromic Luvisol, Calcaric Arenosol, Eutric Cambisol, Vertic Cambisol and Ferric Luvisol.

As there is a general lack of quality weather information accessible in India (refer to Fig. 1) we chose to evaluate two synthetic weather data information in order to increase the coverage of major chickpea production system. For this exercise, two sets of synthetic weather data including MarkSim (Jones and Thornton, 2000; Jones et al., 2002) and AgMERRA (Ruane et al., 2015) were compared with available observed weather data (Tmin, Tmax, rainfall quantity and distribution, chickpea yield simulated based on this information) from 23 weather stations (similarly in Van Wart et al. (2015) Fig. 1). Solar radiation was estimated using algorithm based on information of sunshine hours and extraterrestrial radiation (Soltani and Hoogenboom, 2003a, 2003b; Soltani and Sinclair, 2012b).

The suitability of the synthetic weather records were compared according to i) their correlation with observed T_{max} and T_{min} and sum of rainfall and ii) the kernel density plots expressing both the pattern and amount of each rainfall during the growing season of chickpea using SAS software (v.9.3). iii) Finally, to assess the integrated effect of synthetic data (AgMERRA or MarkSim) on simulations, the mean simulated yields using observed weather data were compared against yields using synthetic weather data belonging to the same locations. The correlation coefficient and the root mean square of error (RMSE) was computed to evaluate the degree of agreement between these data sources (Fig. 3a and b). Based on these three criteria, we continued the