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

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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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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

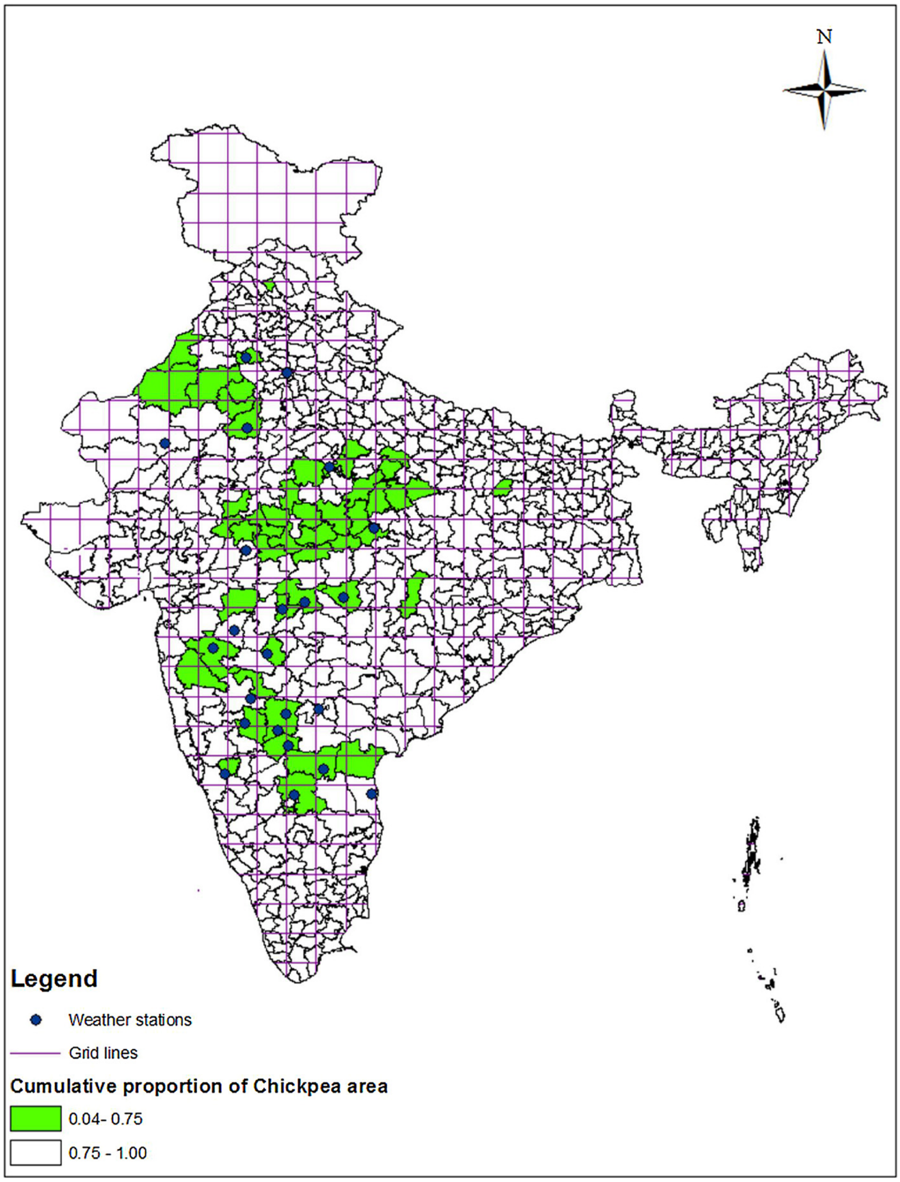

Fig. 1. This map shows 75% of chickpea production area which is highlighted in green and 23 weather stations with available weather records across India. Highlighted area encompasses 49 districts with ~5 M ha of cultivated chickpea area with average yields of 800 kg ha^{-1}. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

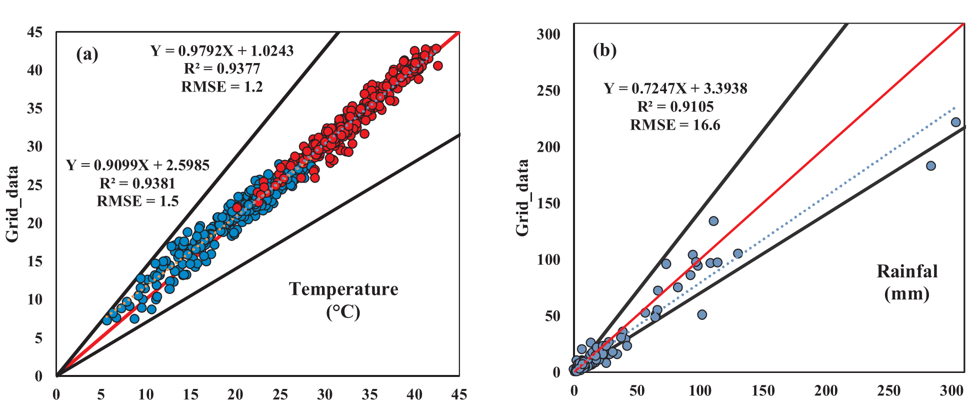

Fig. 2. Comparison of temperature from the synthetic AgMERRA weather dataset with observed temperature (a) and rainfall from the synthetic AgMERRA weather dataset with observed rainfall (b). T_{max} and T_{min} have shown with red and blue color circles, respectively. Rainfall amount is the monthly average for five months of growing season of chickpea (Oct-Feb). Red line is 1:1 line and the black lines showed 30% upper and downer of red one. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

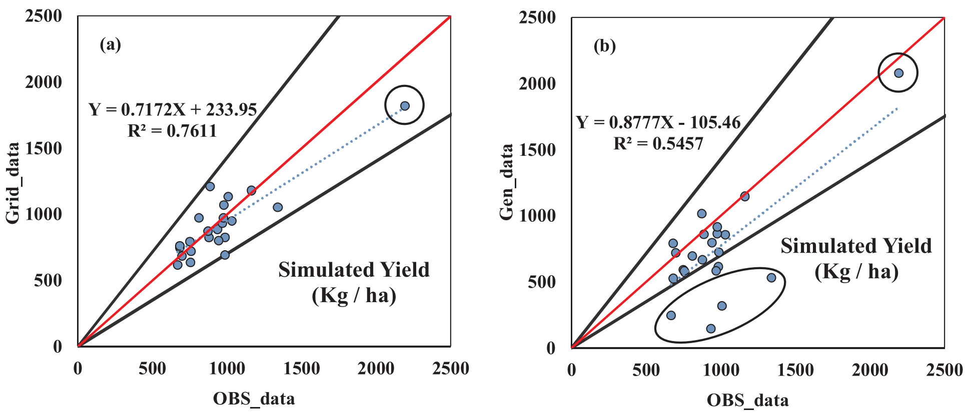

Fig. 3. Comparison of yield by running model with observed weather data versus running model with synthetic data of AgMERRA (a) and MarkSim (b). Four points in the right figure belong to North India stations. The point with high yield is a station in the coastal area of Andhra Pradesh province with high rainfall during chickpea growing season. Red line represents 1:1 line and the black lines harbor 30% upper and lower percentile of 1:1 one. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

work with gridded data of AgMERRA (Figs. 2 and 3, Suppl. Figs. 1–23; refer to result section).

2.3. The crop model

For generating simulated yields, we chose to use a chickpea module of SSM-iLegume-Chickpea model (Soltani and Sinclair, 2011, 2012a) which is a simple mechanistic model earlier used in yield gap analysis of chickpea (Soltani et al., 2016, van Ittersum et al., 2013). SSM-iLegume-Chickpea simulates phenological development, leaf development and senescence, dry matter production and partitioning, plant nitrogen balance, yield formation and soil water balance. This model can capture separate genotypes and their biological responsiveness to environmental factors; solar radiation, photoperiod, temperature, nitrogen and water availability. The model uses a daily time steps to arbitrate the crop, weather and soil information and have the flexibility to simulate management practices (details in Soltani and Sinclair, 2012a). Since far, the model doesn't have capacity to simulate the soil-crop phosphorus dynamics or the effects of pest and diseases. Despite, SSM-iLegume model has been shown highly reliable in studies encompassing the wide range of environments for various legume species including chickpea (Vadez et al., 2012; Vadez et al., 2013; Soltani et al., 2006; Soltani and Sinclair, 2011; Amiri-Deh-Ahmadi et al., 2014), soybean (Sinclair et al., 2014), bean (Marrou et al., 2014), lentil (Ghanem et al., 2015) and groundnut (Vadez et al., 2017).

The necessary model inputs are: i) daily weather information ii) soil information iii) crop management practices and iv) genotype-specific coefficients defining the key biological processes. At the harvest, the grain water content of chickpea is usually around 12%, therefore, the simulated grain yields presented here were also adjusted for this percentage of moisture content (Soltani et al., 2016).

2.4. Simulation set-up and yield gap analysis

Rather than capturing the diversity in of the on-farm crop management practices, the purpose of this modelling exercise was to simulate a broadly valid baseline that reflect the major dynamic characteristics of the chickpea systems. We chose to set such baseline simulation analysis using the recommended chickpea cultivation practices collated from Trivedi (2009), Vittal et al. (2005), and from expert consultation (Table 1). We assumed the soil moisture profile at sowing time was fully charged after the rainy season and also reflecting the common practice of pre-sowing (Trivedi, 2009). Being capable of fixing atmospheric nitrogen through rhizobial symbiosis, chickpea crop requires only a small amount of basal N application for establishment prior to the formation of nodules. This requirement is accounted for by the recommended basal fertilizer dose ~20 kg ha^{-1} of di-ammonium phosphate (Trivedi, 2009; $H(NH_4)_2PO_4$; 18% N content) which equals to initial soil nitrogen content of 2.11 g N m^{-2} as the SSM-iLegume model input.

Table 1
The range of characteristics used for simulations of the main chickpea production region in India.

Management and soil inputs	Conditions
Sowing window	5 October–15 November
Plant density	33 plants m^{-2}
Soil drained upper limit	0.09–0.41 cm cm^{-1}
Soil saturation limit	0.35–0.49 cm cm^{-1}
Volumetric extractable water content	0.10–0.13 cm cm^{-1}
Soil albedo	0.13–0.14
Curve number[a]	73–82
Soil depth	75–180 cm
Initial soil nitrogen	2.11 gr N m^{-2}

[a] Daily runoff (RUNOF, mm) is calculated using a simplified curve number procedure developed by scientists at USDA-Soil Conservation Service (SCS). In the curve number method, daily surface runoff is calculated as a function of daily rainfall (RAIN, mm) and a soil retention parameter (From Soltani and Sinclair, 2012b).

The common sowing window of chickpea in India is conditioned by the harvest of the rainy season (Kharif) crop starting from the early October in the south and later sowing until the last week of November in the northern regions. Late sowing in the north is also necessary to avoid cold temperatures during the flowering time. Therefore, after the discussion with experts, four different sowing dates spanning from 5th October to 15th November were used to reflect the prevailing chickpea cropping systems across the latitudes covered in this study. In general, chickpea cultivated in the northern latitudes is characterized by a long growing cycle which gradually decreases towards the southern regions. To reflect this variability, three different sets of phenology parameters were used across the main production tract (Table 2). These phenology parameters were synthetized and re-iterated from Vadez et al. (2013):

Table 2
Main phenology parameters used in simulation. Reiterated phenology parameters estimates which represent cultivars typically grown in Northern latitudes ("Hisar" cultivar), in Central and some Southern regions ("ICRISAT" cultivar) and JG-11 in the remaining Southern parts were used.

Cultivar	Phenology	
	EMR1[a]	R5R7[b]
Hisar	56.3	43.8
ICRISAT	38.9	30.3
JG-11	36.5	35.0

[a] EMR1, Biological days required between plant emergence and flower appearance (R1).

[b] R5R7, Biological days required between first seed (R5) and physiological maturity (R7).

The “ICRISAT”/“Hisar” cultivars encompass the parameters of popular cultivars grown in Central and some Southern/Northern latitudes (Table 2). For the specific Southern parts of the chickpea production tract, the popular JG-11 cultivar (Gumma et al., 2016) coefficients were re-calculated from the JG-11 specific coefficients existing in DSSAT (Singh et al., 2014). Consequently, the model was run for 30 years of AgMERRA synthetic data to cover the major chickpea cropping area. The simulations provided an estimate of:

1) Potential yield (Y_p); the maximum yield of a crop cultivar grown in optimal water and nutrient supply without biotic stress (Lobell et al., 2009; van Ittersum et al., 2013).
2) Water-limited potential yield (Y_w); reflects the rain-fed cropping conditions when crop is raised without any supplementary irrigation (van Ittersum et al., 2013).
3) Partially-irrigated yield potential (Y_{pi}); represent the records on the irrigation access across the regions in India and is designed to mimic the most probable region-specific irrigation scheme practiced by farmers – in this case one supplementary irrigation (60 mm) at flowering stage (Trivedi, 2009). This system is broadly representative of farmer practice across the regions.

For estimating the yield gap (Y_g), the weighted potential yield (Y_{wp}) was calculated according to the information on proportion of irrigated and rain-fed area of each district:

$$Y_{wp,i} = [(Y_{w,i} \times A_{rainfed,i}) + (Y_{pi,i} \times A_{irrigated,i})] \quad (1)$$

Where, $Y_{wp,i}$ is the weighted potential yield in district i, $Y_{w,i}$ is the water-limited potential yield in district i, Y_{pi} is partially-irrigated yield potential, $A_{rainfed,i}$ is the total rain-fed area of cultivated chickpea in district i and $A_{irrigated,i}$ is the total irrigated area of cultivated chickpea in district i.

Consequently, Y_g is the difference between weighted potential yield (Y_{wp}, equation 1) and average farmers yield (actual observed yield; Y_a):

$$Y_{g,i} = Y_{wp,i} - Y_{a,i} \quad (2)$$

The difference in yield between water limited and water non-limited condition; i.e. the proportion of yield which is lost due to the effect of water deficit was estimated for each district:

$$(Y_p–Y_w)/Y_p \times 100\ [\%] \quad (3)$$

The effect of one supplementary irrigation at flowering stage on yield was also calculated as below:

$$(Y_{pi} - Y_w)/Y_{pi} \times 100\ [\%] \quad (4)$$

2.5. Identification of homogeneous system units (HSU) across production environments

Observed and simulated geo-bio-physical properties of each district described above were used to define the homogeneous system units; i.e. latitude, climate (temperature, rain, ET), soil (WHC, depth), actual yield, crop characteristics (Max LAI, duration of chickpea growing season), simulated yields (Y_p and Y_w), yield gap (Y_g), effect of water deficit and supplementary irrigation and proportion of irrigation. To evaluate the degree of similarities between the districts this information was analyzed by principal component analysis (PCA; R software v.3.2). PCA output indicated the loadings of first 4 components explained majority of the variability existing in the dataset (> 85%). Therefore these 4 loadings specific for each simulation unit were used to further separate these simulation units into 6 clusters. We have confirmed the significant differences between separate clusters using one-way ANOVA. Each of these 6 clusters, therefore, encompassed the districts with comparatively higher similarities in the loaded geo-bio-physical properties (HSUs) and the results were visualized using ArcGIS software v.9.3.

3. Results

3.1. Main chickpea production systems and actual yield (Y_a)

Chickpea is cultivated in about 280 districts across India (around 8 M ha producing 7.5 M tons or ∼0.9 t of grain/ha in the recent decade). However, among this large number of districts, 78 districts encompassed 82% of the total chickpea cropping area (around 5 M ha in recent decades) in the country and so defined the focal area of our study (Fig. 1). Analyzing a 15 years timespan of chickpea cultivation records for this focal area was considered a reasonable base period across which to describe the major production tract in India (van Ittersum et al., 2013). The average Y_a of these 78 districts was 802 kg ha^{-1} with the highest Y_a recorded at the costal districts of Andhra Pradesh (Praksam with 1570 kg ha^{-1}) and the lowest yields were generally attained in Rajasthan districts (Churu with 328 kg ha^{-1}).

3.2. Covering the main production systems with reliable weather information

The suitability of the synthetic meteorological information (AgMERRA/MarkSim) for this particular exercise was assessed by comparing this data with observed meteorological records and by comparing simulated yield outputs of synthetic vs observed meteorological information – i.e. using the virtual plant as a weather data quality indicator (Fig. 3a and b). We found that yield predictions based on observed weather information was best correlated to the simulation that used AgMERRA data (RMSE = 159 kg ha^{-1}; Fig. 3a), compared to those generated with MarkSim data (RMSE = 342 kg ha^{-1}; Fig. 3). The larger RMSE of MarkSim data was mainly caused by inability of MarkSIM data to capture variation in T and rainfall especially in northern latitudes which resulted in overall yield underestimation in these geographies (Fig. 3b). For these reasons we carried out the further modelling analyses with synthetic AgMERRA data.

3.3. Crop production potential and its limitations

Across the diverse environments, the mean of simulated potential yield (Y_p) was 2965 kg ha^{-1} (minimum of 2254 kg ha^{-1} in Fatehpur and maximum of 4432 kg ha^{-1} in Sikar and Hamirpur). Comparatively lower was the mean of simulated water-limited potential yield (Y_w) = 1013 kg ha^{-1} (minimum of 727 kg ha^{-1} in Ajmer and maximum of 1913 kg ha^{-1} in Prakasam). These two estimates (Y_p and Y_w) were used to assess the potential magnitude of yield losses in rain-fed systems specific for particular districts; i.e. yield reduction due to drought reflecting the situation where farmers don’t use irrigation (Fig. 4; the difference between blue proportion of the circles (Y_p) and white proportion of the circles (Y_w). In average, 64% (min 25%; max 82%) of Y_p was lost due to water deficit in the absence of supplementary irrigation. Here, the lowest risk of water deficit was associated with three districts in Andhra Pradesh state, which had generally sufficient in-crop rain and crop was raised on deep soils (Prakasam, Cuddapah and Anantapur, with 24, 36 and 43% water deficit yield loss) whereas over the three quarters of yield potential could be lost due to water deficit in Rajasthan characterized by low in-crop rain and poor sandy soil (Ajmer, Tonk and Sawai Madhopur, with 82, 81 and 79% respectively). Furthermore, we quantified the effect of the common farmer’s practice when the irrigation could be accessed, i.e. one supplementary irrigation at flowering stage. The estimated yield with such irrigation practice (Y_{pi}) was 1872 kg ha^{-1} on average (maximum of 2317 kg ha^{-1} in Praksam and minimum of 1361 kg ha^{-1} in Ajmer) which means that a considerable proportion (up to 55% in some districts) of yield gap caused by drought ($Y_p - Y_w$) could be potentially bridged with one supplementary irrigation ($Y_{pi} - Y_w$).

Finally, according to the specific proportion of irrigated area of each districts within the major chickpea production region, we defined a

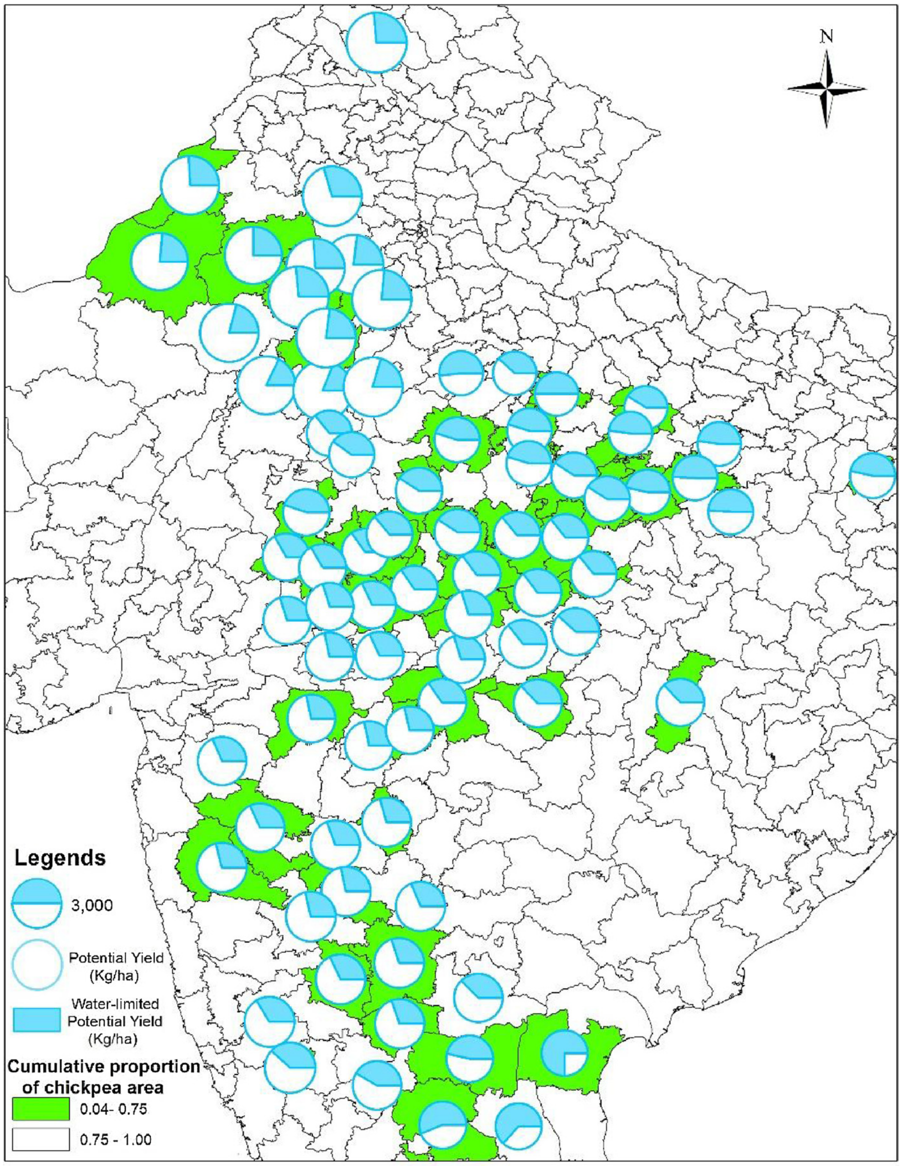

Fig. 4. Green-highlighted districts encompass 75% of chickpea production area in India. The size of the circles is equivalent to the simulated yield potential (Y_p); and the blue proportion of the circles reflects the water-limited yield potential (Y_w). Therefore, the magnitude of yield loss accountable to water deficit is reflected in the size of the white proportion of the circles within each district. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

measure of yield potential attainable with current irrigation practice (i.e. Y_{wp} ~1333 kg ha^{-1} in average which varied between 762 and 1953 kg ha^{-1}). Consequently, we defined the yield gap (Y_g) for each district as a difference between the simulated yield attainable using current irrigation practices (Y_{wp}) and evaluated yield average during recent 15 years (Y_a); $Y_g = Y_{wp} - Y_a$. Y_g was found to vary between 204 and 1194 kg ha^{-1} with an average ~530 kg ha^{-1} (i.e. 20–76% of Y_{wp} with a mean Y_g of 40%; Fig. 5). Fig. 5 points out to the Northern districts of Rajasthan where farmers hardly reached half of the yield potential (Y_{wp}) with frequent records of seasons with complete yield failures. In such cases, where a supplementary irrigation did not fill the yield gap we suggest that other limitations to yield occurred, e.g. pest and diseases. Accordingly, the highest Y_g as percentage of Y_{wp} (76%) was obtained for Churu, Rajasthan (equal to 1036 kg ha^{-1}). Contrarily, the lowest Y_g was observed in Prakasam district in costal part of Andhra Pradesh with 20% of Y_{wp} (equal to 383 kg ha^{-1}).

3.4. Homogeneous chickpea production units within the main chickpea production tract

The above generated information was used to separate the district into units tangible within the breeding programs. For this, the most informative, observed and modelled, bio-geo-physical characteristics (Table 3) for each districts were analyzed using PCA. Such analysis showed that relations between these characteristics could be described by four principal components (PCs) explaining > 85% of variability in this dataset. The loadings for these four main PCs specific for each district were further clustered into 6 geo-bio-physical units unifying the districts with higher degree of similarities – i.e. homogeneous chickpea production system units (HSU, Table 3, Fig. 6); The details of each HSU are summarized in Table 3, visualized on Fig. 6 and the yield gap of these units is captured in Fig. 7;

- 14 districts of Northern Rajasthan (pink HSU #1, Northern India,

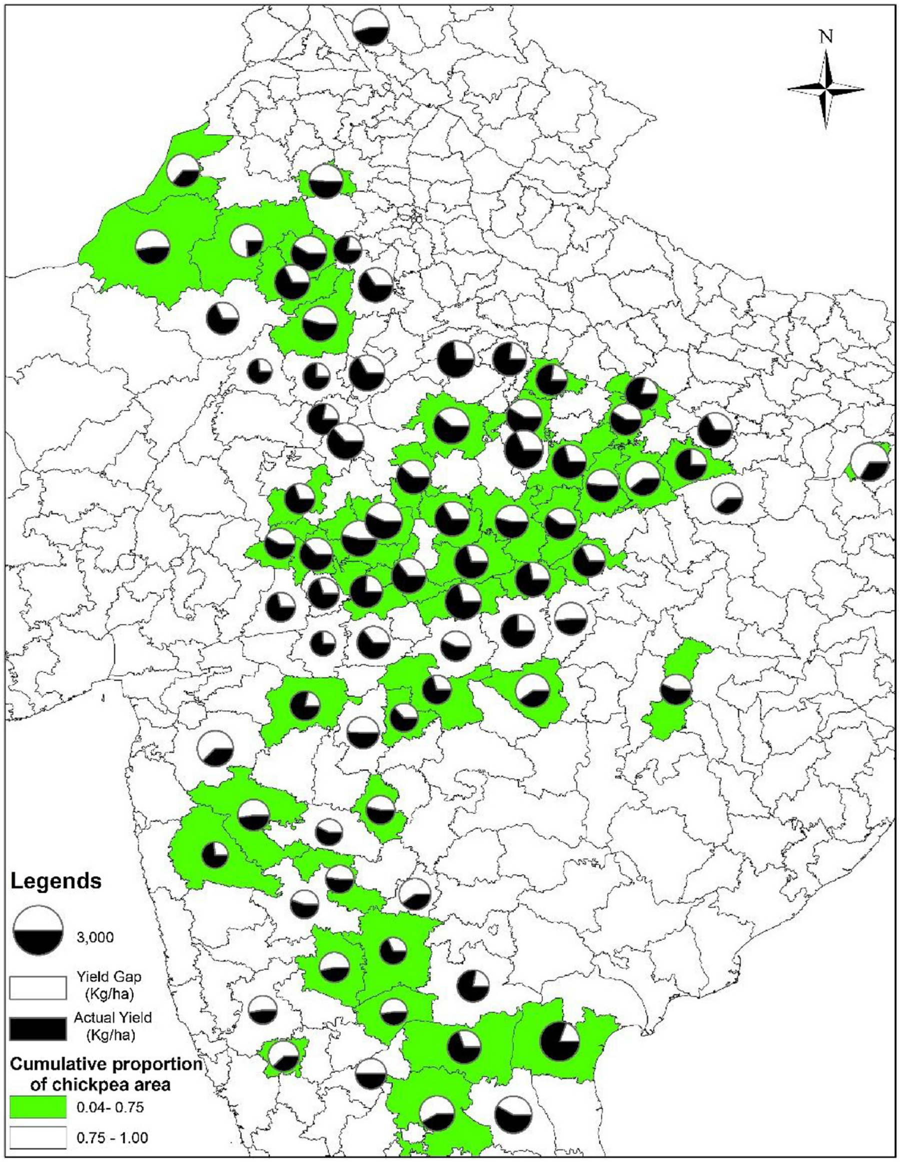

Fig. 5. Green-highlighted districts encompass 75% of chickpea production area in India. The circles indicate the yield gap distribution across the main chickpea production tract in India. The size of whole circles indicate attainable yield with current irrigation practices (Y_{wp}), which takes into account the common irrigation practice at the level of districts. The black portion of each circle indicates the yield attained (Y_a) and the white portion indicates yield gap (Y_g).

23% of investigated area and 20% of production) which experience the lowest in-season temperatures and solar radiation. In this HSU#1, the crop production potential in optimal irrigation practice was found the highest as a result of long growing season and high cumulative radiation during the season, compared to other HSUs (below).

- 19 districts of Northern Madhya Pradesh, Uttar Pradesh and North-East of Rajasthan (green HSU#2, Center-North of India, 25% of investigated area and 29% of production) with relatively high yields but the lowest yield potential.
- 22 districts of Madhya Pradesh (yellow HSU #3, Central India, 29% of investigated area and 32% of production). In this largest HSU#3, the medium yields are attained with large potential production losses due to drought effect as in HSUs #1 and 4 (described below).
- 15 districts of Northern Maharastra and Karnatka (red HSU #4, Central India, 16% of investigated area and 12% of production). The lowest yields in this HSU#4 could be, at least partially, accountable to low incidence of in-season rains and poor soil properties (including shallow soil with low WHC). This is also why the yield loss due to drought with this rain-fed agriculture practices was one of the highest (~ 69%) across HSUs.
- 5 districts of Southern Andhra Pradesh and Southern Karnataka (orange HSU #5, Southern India, 5% of investigated area and 5% of production) with observed yields comparable to HSU#1 and #3 but far shorter growing season and different geographical location.
- 3 districts of Southern Andhra Pradesh (blue HSU #6, South-East coastal India, 2% of investigated area and 3% of production). The highest attained yields in this HSU#6 are likely caused by higher frequency of rains and because the crop is usually raised on deeper soils. This might be the reason why farmers of this region irrigate chickpea crop very rarely.

Fig. 7 shows 80% of modelled yield potential (Y_{wp}) attainable with current management practice which is usually considered the maximum yield that can be realized in the field (Lobell et al., 2009; van Ittersum et al., 2013). In major chickpea production regions of India, closing yield gaps to 80% of Y_{wp} would mean production increase by 40% (1.75 M tons) across 6 major HSUs (Fig. 7; from 71% in HSU#1

Table 3
Main bio-geo-physical characteristics and model outputs of six Homogenous System Units (HSUs) within the main chickpea production tract in India. The different letters following the averages point out to the significant difference in the characters as per results of Tukey-Kramer test. The acronyms used are: potential yield (Y_p); water-limited potential yield (Y_w); actual observed yield; (Y_a) yield gap (Y_g).

Cluster/HSU No.	1	2	3	4	5	6
Character	Average ± SE (Min–Max)	Average ± SE (Min–Max)	Average ± SE (Min–Max)	Average ± SE (Min–Max)	Average ± SE (Min–Max)	Average ± SE (Min–Max)
Investigated area (M ha)	1.31	1.44	1.63	0.91	0.27	0.14
Irrigated area (%)	51	37	45	28	9	9
Current Production (M ton)	0.87	1.27	1.43	0.53	0.20	0.15
Number of districts	14	19	22	15	5	3
Number of dominant soil types	3	3	3	2	1	4
Latitude (degrees)	27. 9 (26.1–31.7)	25.1 (23.9–26.4)	22.8 (21.0–25.5)	18.9 (16.1–21.1)	15.7 (15.0–16.6)	14.9 (14.5–15.5)
Average of Tmin (°C)	10.2 (9.6–11.2)	11.8 (10.5–14.0)	13.6 (12.4–15.0)	16.3 (14.0–18.6)	19.1 (18.0–20.0)	20. 9 (20.1–21.3)
Average of Tmax (°C)	25.8 (25.0–27.3)	26.7 (25.6–27.7)	28.6 (27.0–30.7)	30.3 (27.8–31.6)	30.3 (29.7–30.8)	30.8 (30.4–31.1)
Sum of Radiation (MJ m^{-2})	1702 ± 21.6^{a} (1553–1822)	1388 ± 7.4^{bc} (1318–1459)	1373 ± 6.1^{c} (1317–1455)	1425 ± 4.6^{b} (1384–1447)	1424 ± 21.5^{bc} (1361–1469)	1425 ± 10.8^{b} (1413–1447)
Season rainfall (mm)	27.4 ± 2.4^{d} (13.1–42.2)	27.9 ± 2.7 ^{d} (14.1–43.4)	25.4 ± 1.4 ^{d} (10.4–37.6)	42.7 ± 1.7 ^{c} (31.6–56.1)	60.8 ± 2.6 ^{b} (51.2–65.6)	167.7 ± 44.2 ^{a} (116.1–255.6)
Soil depth (mm)	1607.1 ± 39.9 ^{a} (1500–1800)	1382.1 ± 58.0 ^{c} (1050–1800)	1077.7 ± 16.4 ^{d} (1050–1360)	1070.0 ± 32.3 ^{d} (900–1500)	1290.0 ± 71.4 ^{c} (1050–1500)	1500 ± 0.0 ^{b} (1500–1500)
Water holding capacity	119.9 ± 10.8 ^{b} (92–175.6)	142.37 ± 2.7 ^{a} (125–175)	134.0 ± 1.4 ^{b} (132–154)	130.75 ± 2.4 ^{b} (100–145.3)	146.28 ± 4.2 ^{a} (132–158.4)	145.3 ± 0 ^{a} (145.3–145.3)
Evaporation (E)	36.90 ± 0.4 ^{f} (35–39.8)	42.65 ± 0. ^{e} (39.7–44.8)	46.12 ± 0.5 ^{d} (40.7–53.2)	61.24 ± 1.4 ^{c} (54.1–70.3)	68.16 ± 0.7 ^{b} (66.6–70.4)	100.08 ± 7.6 ^{a} (91.6–115.3)
Transpiration (Tr)	95.26 ± 1.4 ^{c} (86.7–105.9)	91.67 ± 1.3 ^{c} (76.3–97.4)	92.86 ± 0.3 ^{bc} (90.4–95.5)	95.64 ± 0.8 ^{b} (88.4–100.4)	99.19 ± 1.4 ^{b} (96.2–104.3)	108.90 ± 2.3 ^{a} (105.2–113.2)
Evapotranspiration (ET)	132.2 ± 1. ^{e} (122.27–143.95)	134.3 ± 1. ^{e} (116.5–142.0)	139 ± 0.6 ^{d} (131.1–145.6)	156.9 ± 1.4 ^{c} (148.5–166.7)	167.4 ± 2.0 ^{b} (163.2–174.6)	209 ± 9.9 ^{a} (196.9–228.5)
E/ET	0.28 ± 0.00 ^{e} (0.27–0.29)	0.32 ± 0.00 ^{d} (0.30–0.35)	0.33 ± 0.00 ^{d} (0.31–0.36)	0.38 ± 0.01 ^{c} (0.35–0.43)	0.40 ± 0.002 ^{b} (0.39–0.40)	0.47 ± 0.01 ^{a} (0.46–0.50)
Growing season period (d)	123.05 ± 1.7 ^{a} (110.6–131.9)	100.05 ± 0.7 ^{b} (93.5–105.5)	91.14 ± 0.5 ^{c} (86.8–95.5)	86.16 ± 0.65 ^{d} (84.6–91.1)	86.73 ± 0.69 ^{d} (85.3–89.0)	92.16 ± 1.5 ^{c} (90.1–95.1)
Y_p (kg ha^{-1})	4210.3 ± 38.1 ^{a} (3944.5–4432.1)	2448.6 ± 25.9 ^{d} (2255–2624)	2711.8 ± 16.7 ^{c} (2513–2837.8)	2915.8 ± 23.7 ^{b} (2764.7–3044.7)	2916.4 ± 77.1 ^{b} (2677.7–3096.4)	2609.6 ± 48.4 ^{c} (2548.9–2705.3)
Y_w (kg ha^{-1})	994.4 ± 39.5 ^{bc} (727–1254)	1098.3 ± 21.1 ^{b} (881–1213.9)	906.5 ± 14.9 ^{c} (785.1–1030.7)	897.3 ± 16.9 ^{c} (789.8–1029.1)	1148.7 ± 39.3 ^{b} (1034.5–1246.4)	1689.1 ± 116.3 ^{a} (1521.2–1912.5)
Y_a (kg ha^{-1})	771.6 ± 57.1 ^{a} (328.6–1072.6)	916.1 ± 49.9 ^{a} (470.4–1279.4)	859.2 ± 33.8 ^{a} (590.7–1165.9)	580.8 ± 19.5 ^{b} (433.3–751.3)	706 ± 121.1 ^{ab} (447.5–1002.7)	1070.1 ± 269.9 ^{a} (643.6–1570)
Percent of Y_g	42 ± 4.2 ^{ab} (22.2–76)	37.3 ± 3.1 ^{ab} (20.8–66.2)	34.6 ± 1.9 ^{b} (21.1–52.1)	46.4 ± 2.9 ^{a} (27–62.4)	43.4 ± 7.5 ^{ab} (21.8–62.3)	39.9 ± 11.2 ^{ab} (19.6–58.3)
Effect of drought (%)	76.4 ± 0.9 ^{a} (70.5–82.2)	55.1 ± 0.9 ^{c} (48.2–61.7)	66.5 ± 0.7 ^{b} (61.9–71.9)	69.2 ± 0.8 ^{b} (63–71.7)	60.4 ± 2.1 ^{c} (53.5–66.3)	35.1 ± 5.5 ^{d} (25–43.8)
Effect of one irrigation (%)	42.8 ± 1.1 ^{b} (31.8–47.6)	47.6 ± 0.7 ^{b} (43.7–55.1)	50.2 ± 0.3 ^{a} (47.8–53.4)	46.5 ± 1.5 ^{b} (44.3–48.3)	43.4 ± 0.5 ^{b} (41.6–44.6)	24.2 ± 3.9 ^{c} (17.5–31.2)

(~0.62 M tons) to 25% in HSU#3 (~0.37 M tons)).

4. Discussion

Food security largely depends on our capacity to develop effective strategies for sustainable and equitable agricultural systems' intensification which needs to be clearly focused and the putative agro-interventions designed accordingly. India, the world leader in chickpea production, produces approximately 12 times more chickpea compared to the second-largest producer, Australia (FAO, 2016). Nonetheless, the demands of a rapidly growing population are not met in India (Ali and Gupta, 2012), therefore, requires an extra capacity to produce chickpea. Here we argue that further production improvement could be achieved only if we characterize the main production systems, quantify their production limitations and point-out to system-specific interventions. To set the baseline for classification of the crop production regions we used the geo-bio-physical information combined with the grain yield gap analysis approaches (van Ittersum et al., 2013) which allowed to separated the main chickpea production areas into authentic homogeneous environment-management-socio-economic context ("homogeneous system units", HSU). Such a framework could be further used to predict and quantify the effect of HSU-specific agri-interventions and recommend the most promising ones for the on-ground testing (Chenu et al., 2011; Chauhan and Rachaputi, 2014).

4.1. Traditional chickpea production mega-environments and methods used for their refinement

In India, three main chickpea production "mega-environments" are usually considered in breeding programs, although these are quite loosely defined: North, Central, and South as defined by Vittal et al. (2005), Trivedi, (2009) and personal communication. We argue that the classification of the main chickpea production tracts in three mega-units needs to be refined in order to efficiently support crop improvement programs by developing effective agro-interventions for well-defined chickpea productions units.

Being a crop grown on residual moisture (post-rainy season, rabi), most of the chickpea production area in India is characterized by a late season water deficit which is usually referred to as the major chickpea production limiting factor in India and across the world (Soltani et al., 2016; Singh et al., 2014; Soltani and Sinclair, 2012a; Berger et al., 2004). In this study, we were able to capture such variability, quantify the major limiting factor (water stress occurrence) and its effect on yield by the crop model at the level of districts.

Based on these district level characteristics we defined bio-geo-physical units with higher degree of homogeneity allowing sensible targeting of agro-interventions (i.e. single agro-intervention with presumably similar effect across the unit) using principal component analysis (PCA; similarly in Chauhan and Rachaputi, 2014). PCA-based approach proved appropriate since it accounted for the multi-dimensional characters relations and associated these relations into the set of components which were consequently used for cluster analysis. According to the similarities in the PC-loadings, the districts have been clustered into 6 significantly different homogeneous system units (HSUs). Such an information will be particularly valuable to strategically and efficiently choose the representative breeding material evaluation sites (i.e. "multi-location trials"; Chauhan and Rachaputi (2014)).

4.2. Main production limitations within homogeneous system units (HSUs) and future perspectives

Our study encompassing major chickpea production tract in India confirmed that the potential yield losses due to water deficit in rain-fed areas were, indeed, severe (64% in average) but the range of losses largely varied regions (HSUs; ~35–80%). Therefore, to design effective interventions one has to have the necessary insight into whether a particular bio-geo-physical system where the crop production takes place should be focused on agricultural intensification practices (e.g. increasing planting densities, fertilization) or rather on drought alleviation interventions (e.g. developing adapted cultivars, specific management). Our study, clearly disaggregated between the HSUs wherein the rain-fed agricultural practices call for conservation interventions and HSUs where the production potential is altogether the main factor limiting the production;

Under the rain-fed agricultural practice in HSUs 1, 3 and 4, the potential yields (~950 kg ha^{-1}) and potential yield losses due to drought were estimated to be more severe (~70%) compared to remaining HSUs. Likely for this reason, the one supplementary irrigation was practiced more often (~40% of area) and could rescue ~45% of yields (~450 kg ha^{-1}) in these HSUs 1, 3, 4. The proportional yield losses due to drought (~60%) and the water-limited potential yields in HSU 5 were comparable to HSU 2 (~1100 kg ha^{-1}), nevertheless, only a small proportion of HSU 5 areas were under irrigation (< 10%, 0.03 M ha) although saving significant proportion of yield (~43%, 880 kg ha^{-1}). Therefore, altogether in the rain-fed conditions in these HSUs (1, 3, 4 and 5) the potential effect of drought appears to be more severe and these should be the frontline focal area likely benefiting from optimized crop management (e.g. sowing window), improved water-conservation practices (e. g. using straw mulch of previous crop to reduce evaporation from soil or using organic manure to increase WHC of the soil) or introduction of drought adapted cultivars (e.g. short duration crop; extra-early varieties maturing in 85–100 days at Patancheru are now available (Gaur et al., 2015), or lines with restricted transpiration under high evaporative demand (Zaman-Allah et al., 2011)). Production benefits of early maturing cultivars in selected regions of HSUs 3, 4, 5 were already shown by Berger et al. (2006). The potential benefits of suggested agri-interventions can be now tested in-silico and justify further investment into the conservation agricultural practices for these rain-fed areas.

Compared to rain-fed areas of HSUs 1, 3, 4 and 5 the production across HSU 6 (i.e. low Yg with low effect of drought and supplementary irrigation) was clearly limited by the cultivar production potential. This might be also the case of HSU 2 with the lowest yield potential (~2500 kg ha^{-1}) but comparably higher yield realized (Y_a; Table 3). This still means that water stress of rain-fed areas within HSU 2 might be the problem, although to a lower extent compared to HSUs 1, 3, 4 and 5. Such results may also signify there could be other reasons for yield losses which we didn't capture in the model and which might be common with neighboring HSU 1 where severe biotic stress, early season cold stress and late seasons heat stress are being frequently reported (Vittal et al., 2005; personal communication with experts). Altogether, HSU 6, 2 and irrigated areas of remaining HSUs may rather benefit from agricultural intensification practices (e.g. longer duration, higher vigor, increased plant population). Berger et al. (2006) already confirmed that later flowering would be necessary to maximize mass accumulation and delay pod set until temperatures rise sufficiently to prevent abortion in Northern regions (HSUs 1, 2).

The model set-ups developed in this work provide the necessary baseline to enable testing the effects of particular interventions, e.g. whether the change in crop phenology or crop growth habitus, crop planting densities and irrigation practices could bring desired yield improvement in, now well-defined, HSUs. Same modelling framework shall further help to analyze whether it would be economically viable to develop separate interventions for rain-fed/irrigated areas within these HSUs.

4.3. Potential draw-backs associated with adapted approaches

Despite the presented work engaged the chickpea production system experts since the beginning and the results appeared well-aligned with the on-ground reality, there are potential draw-backs associated with the adopted approach; i.e. i) We have used the mechanistic crop-model

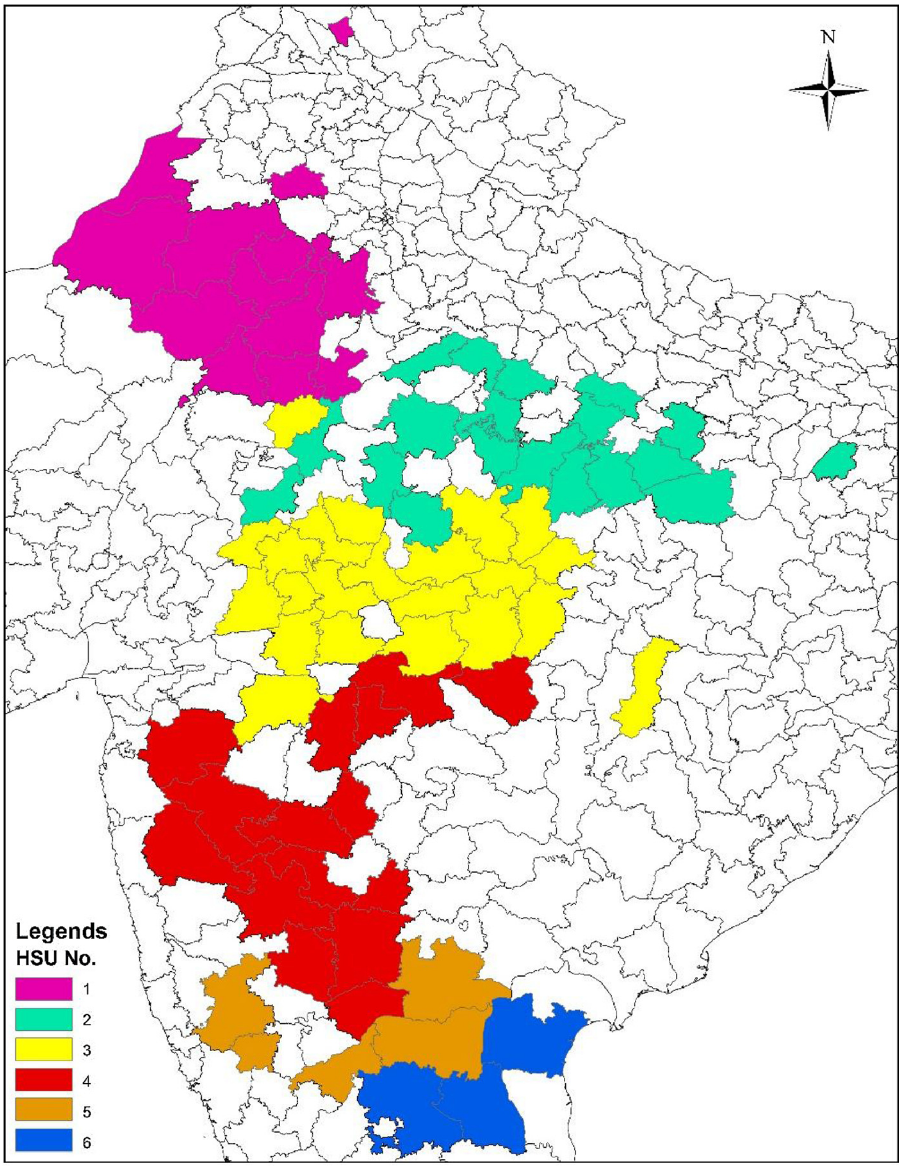

Fig. 6. Results of clustering analysis which separated districts within the main production tract in India (highlighted with colors) into six Homogenous System Units (HSUs) with higher degree of similarities in their observed and modelled bio-geo-physical characteristics. The highlighted districts encompass 82% of chickpea production area in India.

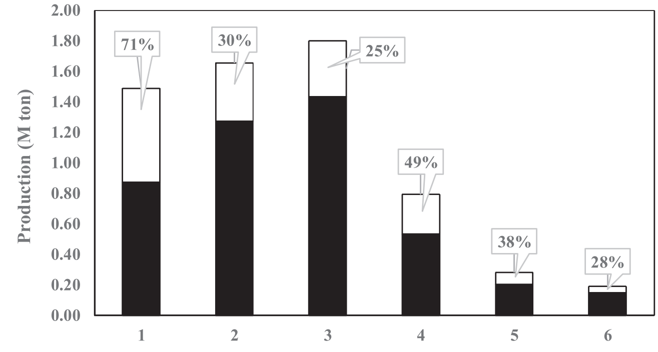

Fig. 7. Bar chart shows the average of current chickpea production between 1996 and 2010 (dark parts) and percentage of production increase needed to achieve 80% of Y_{wp} (white parts) within each of the identified Homogeneous System Unit (HSU).

SSM-iLegume-Chickpea which proved robust to capture dynamics of chickpea production systems before (Vadez et al., 2012; Vadez et al., 2013, Soltani et al., 2006; Soltani and Sinclair, 2011; Amiri-Deh-Ahmadi et al., 2014) and we adapted some of the model set-ups from these studies. However, we are aware the model doesn't simulate pest and disease outbreaks, plant-phosphorus dynamics and the functions to capture cold and heat responses are very basic. ii) Also, the purpose of this work was to set the baseline modelling framework rather than dissection of granularities in GxM practices used by farmers (which will be, anyways, the topic for consequent studies). At this level of system analysis, assumptions have been made and are described in materials and methods. Therefore, it might be possible that some of the characteristics and tools used to describe chickpea system dynamics were too generic and might have distorted the consequent analyses. Nevertheless, the laid framework will be available at www.dataverse.org and www.gems.icrisat.org, open for improvements and its sensibility shall be practically proof-tested in engagement with breeding programs in the near future.

5. Conclusions

In this work we aimed to develop the analytical tools and baseline framework to assist the decision-making process in chickpea crop improvement programs. For this purpose, we gathered sensible geo-bio-physical information on the major chickpea production districts in India, reconstructed the system dynamics using the SSM-iLegume model and characterized these regions and their specific production constraints employing the yield-gap approach. We found that under the given irrigation availability, India has the capacity to produce straight 40% more chickpea (~1.75 M tons) under the scenario where the recommended crop management practices would be implemented. We also quantified the whole-India potential yield-loss due to drought was large but there was also a large variability in potential drought-related yield losses between the investigated districts (~35–80%). This gathered bio-geo-physical data and modelling outputs enabled rigorous, data-driven, quantitative re-definition of production environments showing that the classical partitioning into the three rather intuitive North-Central-South "mega-environments" was too crude to represent effective "breeding targets" and couldn't possibly support the decision-making processes strategic for crop improvement programs. The results emphasized that the Indian chickpea tract was much more heterogeneous and the effective system interventions will have to be designed for diverse context of six homogeneous system units (HSUs) identified in this work but may also consider the specific situation in the regions with/without irrigation access. The baseline modelling set-up, identified HSUs and understanding of chickpea production system heterogeneity developed in this study is intended to be further proof-tested as a decisions-making system in support of the chickpea improvement programs.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.fcr.2018.03.023.

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