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Crop simulation analysis of phenological adaptation of chickpea to different latitudes of India

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ABSTRACT

Plant phenology is a critical component of crop adaptation, especially under environmental conditions that don't allow crop growth for unlimited periods. In chickpea (*Cicer arietinum* L.), which faces terminal drought and increasing temperature at the end of its growing season, it is widely considered that longer duration genotypes are needed for the higher latitudes of India and shorter duration genotypes for lower latitudes. Here, we compare two sets of genotypes bred in two locations varying in latitude (high latitude: Hisar, Haryana, India; low latitude: ICRISAT, Andhra Pradesh, India) for the number of biological days from emergence to flowering (EMR1) and for the grain filling period (R5R7). Biological days referred to days where the phenological development was optimal and therefore provides a measure of thermal time. Using a robust crop simulation model, the optimum EMR1 and R5R7 were determined for various locations. As expected, EMR1 and R5R7 values of genotypes bred for low latitude were lower than those bred for high latitude. However, predicted yields of these two sets of genotypes were similar when simulated for each of the two environments, yields being overall higher at Hisar. Results for the combined set of genotypes at each location predicted a similar optimum EMR1 to achieve maximum yield at each location: 44.3 biological days at Hisar and 43.5 biological days at ICRISAT. Derivation of optimum EMR1 across a total of ten locations in India indicated a wider range (37.2–51.8 biological days), although in eight locations the optimum EMR1 was in a narrower range (39.4–47.3 biological days). The differences in EMR1 across locations did not correspond to their latitudinal differences. Instead, rainfall through the growing season was significantly and positively related ($R^2 = 0.55$) to optimum EMR1. These results indicate that the breeding for optimum EMR1 of chickpea in India needs to be focused on expected rainfall for a region, and that an optimum EMR1 of about 43 biological days would likely fit most of the environments.

1. Introduction

Plant phenology is an important aspect of crop adaptation to environmental conditions in order to match optimally the cropping cycle with the seasonal weather pattern. Phenology has particular importance in water-limited situations where the cropping cycle has to match seasonal variability in available soil water. For chickpea cultivation in tropical areas, it is widely assumed that chickpea varieties differing in their duration need to be developed for adaption to different latitudes (Saxena, 1984; Kumar and Abbo, 2001; Berger et al., 2011). In India, where terminal drought is the major limitation to yield, it is then considered that longer duration genotypes are more adapted to higher latitude, whereas shorter duration genotypes are better adapted to lower latitudes (Berger et al., 2006). The rationale is that the higher latitude usually has cooler temperature until at least March, and longer duration cultivars can sustain CO_2 accumulation and fill grain for a longer period before summer temperatures become too high (Saxena et al., 1996; Khanna-Chopra and Sinha, 1987). By contrast, in southern India the chickpea crop duration window is constrained by sowing at the termination of rains (later October) and increasing heat of summer (early March), resulting in a narrow window for shorter duration cultivars. For southern India, breeding for earliness has been widely recommended (Saxena, 1984; Kumar and Abbo, 2001; Berger et al., 2004).

The difficulty in adopting the concept of latitude-adapted cultivars is that there is limited experimental evidence in India based on comparisons of short- and long-duration genotypes over a range of latitudes. Often breeding programs from the North India report the testing of their long-duration lines, whereas breeding programs from the South report the testing of their short-duration material

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(Saxena, 1984). Berger et al. (2006) noticed this major problem and attempted to fill that gap by testing a fairly large set of lines, varying in duration, across a range of locations varying in latitude, in order to assess whether there is specific phenological adaptations of chickpea to different latitudes. Their conclusion, based on analysis of the experimental data, sustained the original hypothesis in selecting cultivar phenology based on latitude.

However, there were at least three limitations in the study of Berger et al. (2006). First, the low-latitude region was represented only by a single location in the South situated at 17° N, whereas all the other locations were between 23° N and 29° N. This is particularly important in the current context since there has been increasing cultivation of chickpea in southern locations (around 17–18° N latitude). Therefore, the question is whether the conclusion of Berger et al. (2006) was limited by having results from only a single low-latitude location. Also, some of the most northern locations where chickpea is grown (e.g. Amritsar) were not included. Second, the analysis of Berger et al. (2006) was based simply on days to flowering. In comparing phenological development across location it is important to take account of dynamic changes in temperature during development. That is, the rate of phenological development toward flowering for example is highly dependent on the daily temperature environment. Cultivar comparisons across latitudes need to account for the temperature environment and the developmental differences among cultivars in their response to temperature, as recently shown (Berger et al., 2011). Third, there is ambiguity between their main conclusion of the need to select cultivar duration with regards to location latitude, and their report of a cluster of medium duration genotypes reaching the highest yield across all latitudes (Berger et al., 2006).

The sensitivity of phenology in chickpea as a function of temperature and photoperiod is well documented (Ellis et al., 1994; Soltani et al., 2006a,b). Soltani et al. (2006a) reported for several chickpea cultivars their baseline and optimal temperature for phenological development, as well as critical photoperiod. The critical photoperiod was consistently at 11 h indicating for this long-day species that the rate to flowering was delayed at shorter daylengths. While this was an important consideration in the studies of Soltani et al. (2006a) in Iran where the critical photoperiod was often exceeded, at the low latitude of India with shorter photoperiod the influence would be less important. In any case, in the higher latitudes in India where temperatures are cooler than in the south and there is the possibility of some daylengths slightly shorter than 11 h, environmental conditions can have a large influence on expression of cultivar phenology. Further, soil water deficit accelerates phenological development in chickpea (Singh, 1991; Soltani et al., 2001; Soltani and Sinclair, 2011). Therefore, it is essential to account for these environmental variables when attempting to assess the optimal phenological traits over a range of latitudes.

It is now possible to undertake a phenological comparison across cultivars and latitudes by using crop simulation models. A robust model for chickpea exists that accounts for the influence of temperature, photoperiod, and soil water content on phenological development of individual genotypes (Soltani et al., 1999; Soltani and Sinclair, 2011). The model has successfully been tested using independent data from a wide range of growth and environmental conditions (Soltani and Sinclair, 2011). Vadez et al. (2012) have also successfully tested the model performance in response to water deficit under Indian conditions using the data from three line-source experiments which provided a range of water availability. Soltani et al. (2006a,b) have confirmed the robustness of the phenology submodel of the chickpea model under a wide range of environmental conditions that influence phenological development.

This model was used to address three objectives. First, evaluate the thermal time requirement of various genotypes in the development rate during specific phenological stages (i.e. EMR1, time from emergence to flowering, and R5R7, duration of seed filling). This was done by determining the cumulative temperature units (often referred to as "degree day" even though time is not an explicit component of this term) for individual genotypes using observations from a northern (Hisar, Haryana, India) and a southern location (Patancheru, Andhra Pradesh). Second, the range of EMR1 and R5R7 values among genotypes was used to assess the sensitivity of yield to variation in these parameters. The range of variation in the optimum values for these two parameters across locations in India was then assessed. Third, having found variation among locations in the optimum EMR1, the environmental variable accounting for the need for differing EMR1 was studied.

2. Materials and method

2.1. Crop model

The chickpea model of Soltani and Sinclair (2011) was used in this study. The model simulates phenological development, leaf development and senescence, mass partitioning, plant nitrogen balance, yield formation and soil water balance. Responses of crop processes to environmental factors of solar radiation, photoperiod, temperature, nitrogen and water availability, and genotype differences were included in the model. The required model inputs include soil information, crop management and daily weather data. The status of the crop is updated in the model using daily time steps. The model has successfully been tested using independent data from a wide range of growth and environmental conditions (Soltani et al., 2006a; Soltani and Sinclair, 2011). In testing the model, observed days to maturity have been varied from 78 to 228 d and observed grain yield were between 20 and 325 $g\,m^{-2}$. In most cases, simulated phenology and grain yield were similar to observed ones.

This model accounts for the effects of temperature, photoperiod and water deficit on phenological development of chickpea. The phenological stages of emergence, first-flower (R1), first-pod (R3), beginning seed growth (R5), first-maturity (R7) and full-maturity (R8) are predicted by the model (Soltani et al., 2006a,b). Phenological development is predicted using biological day requirements between stages (Soltani and Sinclair, 2011). Biological day requirement is the minimum calendar days between events under optimal temperature, photoperiod and water conditions. Soil stress indeed hastens phenological development (Singh, 1991; Soltani et al., 2001). Optimal temperature is the temperature that allows the maximum phenological development rate. Maximum development rate takes place between a lower and a higher optimum temperature. Below the lower optimum and above the higher optimum temperature, phenological development is less than maximum and is decreased by the appropriate temperature response function described below. Therefore, the concept of biological days refers to a thermal time accumulation and does not equate to a calendar unit. The more familiar cumulative temperature unit for a phenological event is then equal to biological days multiplied by the difference between optimum and base temperatures. Biological days are required in the model for the periods of sowing to emergence, emergence to R1, R1–R3, R3–R5, R5–R7 and R7–R8. Except for the periods of emergence to R1 (EMR1) and R5–R7 (R5R7; grain filling period), the biological day requirements are fairly constant among genotypes (Soltani et al., 2006a,b).

Cardinal temperatures were set at 2 °C for base temperature, 21 °C for lower optimum temperature, 30 °C for upper optimum temperature and 40 °C for ceiling temperature (Soltani et al., 2006a,b). A linear–plateau (2-piece segmented) function is used to account for the effect of photoperiod on development rate.