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# Potential effects of individual versus simultaneous climate change factors on growth and water use in chickpea

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## Abstract

It has been reported that in different regions and sowing dates, the response of crops to past climate change is not the same, due to different rates of decrease/increase in each climatic variable at different regions and months of year. This study was aimed to assess the effect of individual versus simultaneous changes in solar radiation (S), precipitation (P) and temperature (T) on rainfed- and irrigated-chickpea, using model CYRUS. The observed weather data for year 2004 in Kermanshah, Iran, was used as the control. Firstly, the responses of chickpea to individual changes in S and P (25, 50, 75, 125 and 150%) and T (±1, ±2$^{o}$C) with respect to control were studied. Secondly, S, P, and T were simultaneously changed by 50%, 150%, and ±2°C, and the interactions were analyzed. Results indicated that the value of change in biomass, harvest index (HI) and evapotranspiration (ET) was higher for S, compared to P and T. For irrigated-chickpea, the biomass and ET were directly, but HI (nearly) inversely affected by S. T had no impact on HI and ET. The biomass was slightly lower for warmer T. When T, S and P were simultaneously changed, P and T slightly interacted with huge effect of S. For rainfed-chickpea, it was found non-linear response to S for biomass, but linear response for HI. For high S levels, ET was same as control. The decreased levels of P positively affected biomass and HI. There was proportionally change in biomass and HI with changing T. It was found various considerable interactions between variables for biomass, HI and ET. For example, when T was cool, high values of S and P synergistically decreased biomass. These single- and interaction-based results would be adapted as one possible scenario of multi-parameter sensitivity analysis, and could be useful for identifying appropriate management/genotypes for future climate.

***Keywords:*** Chickpea; Climate change; Sensitivity analysis.

## Introduction

Studies of climate change impacts on agriculture initially focused on rising $CO_2$ levels (Curry et al., 1990). There are many reports for both the negative and the positive effects of $CO_2$ increase in plants (e.g., Curtis and Wang, 1998). Studies such as Hansen et al. (2002) and Pielke et al. (2003) suggest that additional aspects of climate including precipitation, temperature and solar radiation need to be studied to assess the impact of climate change, beyond the $CO_2$ increase, on crops.

It is globally accepted that precipitation is a leading factor affecting, especially, rainfed crops yield (e.g., Izaurralde et al., 2003). There are conflicting reports for change in precipitation during last century in different countries/regions. For example, in long-term mean precipitation, a decreasing trend of about -4.1 mm/month/100 years has been reported in boreal Asia. The largest and most statistically significant change has been a decline in rainfall in the winter–rainfall-dominated region of the far southwest of western Australia, where in the period 1910–1995, winter (June–July–August) rainfall declined by 25%, mainly during the 1960s and 1970s (Smith et al., 2000). On the other hand, in Central America, for much of the period from the early 1940s to 1995, western Mexico has experienced an increasingly erratic monsoonal rainfall (Douglas and Englehart, 1999). Annual precipitation trends in past century are characterized essentially by enhanced precipitation in the northern half of Europe, with increases ranging from 10 to close 50% (Dore, 2005).

Temperature changes can affect crop productivity (Fiscus et al., 1997). Higher temperatures may increase plant carboxilation and stimulate higher photosynthesis, respiration, and transpiration rates. Meanwhile, flowering may also be partially triggered by higher temperatures, while low temperatures may reduce energy use and increased sugar storage (Mera et al., 2006). Reddy et al. (2002) concluded that the rates of plant growth and development would continue to increase in the southern U.S. because of enhanced metabolic rates at higher temperatures, combined with increased carbon availability. Changes in temperature can also affect air vapor pressure deficits, and consequently the water use in agricultural landscapes (Kirschbaum, 2004). This may affects transpiration and can cause significant shifts in temperature and water loss. These feedbacks contribute to regional changes in precipitation and cloudiness, leading to changes in solar radiation (Pielke et al., 2003).

Although, there is general agreement for global warming, the rate of increase in temperature has been different in various countries/regions, and even in seasons. For example, the reports for Australia indicate that during the period between 1910 and 2000, average temperature has been increased 0.76 $^oC$ (McInnes et al., 2002). Lu et al. (2006) reported that the increasing trend of temperature is most considerable in the winter and early spring. It should be noted that in some regions, like Atlantic, Canada, it has been decreasing trend in temperature (Skinner and Gullett, 1993).

The solar radiation has an important role in photosynthesis and crop productivity. There is more evidence for decreasing trend in radiation. For instance, Stanhill and Moreshet (1992) after analyzing data of 45 actinometric stations for the years 1958, 1965, 1975, and 1985 indeed found a statistically significant worldwide decrease of global radiation averaging 5.3% (across 27 years). The decline was largest between 45 and 30 $^oN$. Regional declines have been also reported for the western as well as eastern sections of the former Soviet Union (Abakumova et al. 1996; Russak, 1990).

As mentioned, the rate of decrease/increase in climatic variables has been not the same for various regions and seasons; therefore, there are various combinations of precipitation, temperature and radiation, and consequently various response of phenology (e.g., Lu et al., 2006; Sadras and Monzon, 2006), and yield (which has been not assessed as like as phenology) to past climate change in the world. As it was shown by many researchers (e.g., Carbone et al., 2003; Drake et al., 1997; Eastman et al., 2001; Ham et al., 1995; Kirschbaum, 1994; Idso and Idso, 1994), assessment of the role of multiple effects and isolation of individual impacts, and therefore, detecting the relative importance of each climatic variable change in affecting crop performance, are significant in the effects of climate change on plant response. The response of crops to elevated $CO_2$ levels when exposed frequently to water stress or changes in climatic factors such as temperature or rainfall may provide inconsistent results because of the feedback between hydrology and nutrient relations (Deepak and Agrawal, 2001; Drake et al., 1997; Ham et al., 1995; Idso and Idso, 1994; Rosenberg, 1992; Samarakoon and Gifford, 1996). Based on these considerations, and as it was done by Mera et al. (2006) for soybean and maize, our objective in this study was to assess and analyze the individual and multiple interactions of radiation, temperature, and precipitation changes on the regional productivity of *Cicer arietinum*, using simulation.

## Materials and methods

### *Model description*

We used the model CYRUS, which was recoded in Qbasic programming language, for investigating the responses of chickpea to individual and simultaneous changes in three climatic variables. This model was initially designed in 1999 by Soltani et al. (1999). Then it was developed for seedling emergence (Soltani et al., 2006e), for leaf expansion and senescence (Soltani et al., 2006c), for response of leaf expansion and transpiration to soil water deficit (Soltani et al., 2000), for response to photoperiod (Soltani et al., 2004a), for harvest index (Soltani et al., 2005), for phenological development (Soltani et al., 2006a), and for nitrogen accumulation and partitioning (Soltani et al. 2006b). This model has been used for some simulation studies/investigations (Gholipoor and Soltani, 2005a, b; Gholipoor and Soltani, 2006; Gholipoor et al., 2006a, b).

Briefly, in seedling emergence sub model of CYRUS, emergence response to temperature is described by a dent-like function with cardinal temperatures of 4.5 (base), 20.2 (lower optimum), 29.3 (upper optimum) and 40°C (ceiling temperature). Six physiological days (i.e., number of days under optimum temperature conditions; equivalent to thermal time of 94 °C-days) are required from sowing to emergence at a sowing depth of 5 cm. The physiological days requirement is increased by 0.9 days for each centimeter increase in sowing depth. Snow cover effect is considered on the basis of daily maximum and minimum temperatures, as presented in Ritchie (1991).

In leaf sub model, cardinal temperatures for node appearance are 6.0°C for base, 22.2°C for optimum and 31.0°C for ceiling temperature. Leaf senescence on the main stem starts when the main stem has about 12 nodes and proceeds at a rate of 1.67% per each day increase in physiological day (a day with non-limiting temperature and photoperiod). Leaf production per plant versus main stem node number occurs in two phases; phase 1 when plant leaf number increases with a slower and density-independent rate (three leaves per node), and phase 2 with a higher and density-dependent rate of leaf production (8–15 leaves per node).

Phenological development is calculated using multiplicative model that include a dent-like function for response to temperature, and a quadratic function for response to photoperiod. Photoperiod-sensitivity is considered to be different in various cultivars, and cardinal temperatures for phenological development are 0°C for base, 21°C for lower optimum, 32°C for upper optimum and 40°C for ceiling temperature. The cultivars require 25-31 physiological days from E (emergence) to $R_1$ (flowering), 8-12 from R1 to R3 (pod initiation), 3-5 from R3 to R5 (pod filling), 17-18 from R5 to R7 (pod yellowing) and 6 from R7 to R8 (physiological maturity).

The biomass production is calculated based on extinction coefficient (KS) and radiation use efficiency (RUE). It assumes that KS is not radiation- and plant density-dependent. The RUE assumes to be constant (1 g $MJ^{-1}$) across plant densities, but not across temperatures. After correction of RUE for temperature, it is not affected by either solar radiation or vapor pressure deficit (VPD). The partitioning of biomass between leaves and stems is achieved in a biphasic pattern before first-seed stage. After this stage, the fixed partitioning coefficients are used for calculating biomass allocation.

Despite of many simulation models in which the linearity of harvest index increases has been used as a simple means to analyze and predict crop yield in experimental and simulation studies (see Soltani et al., 2005 and related references for more detail), the CYRUS model assumes that its increase is biphasic with turning point temperature equal to 17°C. The similar approach has been proved to be appropriate for application in wheat (Soltani et al., 2004b).

The relation between total N and total biomass throughout the growth period is based on non-linear segmented model (with two segments/phases). Therefore, the rates of N accumulation during phase 1 and 2 are different, and the turning point between two phases of N accumulation is considered 218.3 g biomass per $m^2$. The distribution of N to different parts of plant is calculated using appropriate functions and coefficients.

In soil water balance sub model, daily soil water content is estimated as fraction transpirable soil water (FTSW, which ranges from 0 to 1) to calculate the degree of water limitation experienced by the crop. Similar to that described by Amir and Sinclair (1991), it accounted for additions from infiltration, and losses from soil evaporation, transpiration and drainage. Infiltration is calculated from daily rainfall less any run-off. Run-off is estimated using the curve number technique (Knisel, 1980). Soil evaporation (Ev.) is calculated using the two-stage model as implemented in spring wheat model developed by Amir and Sinclair (1991). Stage I Ev. occurs when water present in the top 200 mm of soil, and FTSW for the total profile is greater than 0.5. Stage II Ev. Occurs when the water in the top layer is exhausted or the FTSW for the total soil profile reaches to less than 0.5. In stage II, Ev. is decreased substantially as a function of the square root of time since the start of stage II. The calculation of Ev. is returned to stage I only when rain or irrigation of greater than 10 mm occurs. Like procedure of Tanner and Sinclair (1983) and Sinclair (1994), the daily transpiration rate is calculated directly from the daily rate of biomass production, transpiration efficiency coefficient (=5 Pa) and VPD. The calculation of VPD is based on suggestion of Tanner and Sinclair (1983) that it to be approximately 0.75 of the difference between saturated vapor pressure calculated from daily maximum and minimum temperatures.

### *Treatments and attributes*

The weather data of year 2004 for Kermanshah ($34^{o}$ 21’ N, $47^{o}$ 7’ E and 1318 m asl), Iran, was used as control meteorological data (Figure 1; values were presented only for growing period of chickpea). Data set contained daily values for sunshine hours, maximum temperature, minimum temperature and rainfall. Solar radiation data were calculated from sunshine hours and extraterrestrial S as outlined by Doorenbos and Pruitt (1977). The cultivar was Beauvanij which is cultivated in the mid west of the country (Kermanshah and Kurdistan provinces).

The control meteorological data were modified as follows: For precipitation (P) and radiation (S) changes, it was altered by 25, 50, 75, 125 and 150%, and for temperature (T) changes of ±1°C and ±2 °C of the control. Similar to Mera et al. (2006), eight additional runs were performed to analyze the effects of simultaneous interaction between the changes in all three variables for ±50% of control S and P, and ±2 °C of the control T. To understand the effect of individual as well as simultaneous changes in S, T and P, a statistical/factorial design of an experiment based technique was used as (Mera et al., 2006; Stein and Alpert, 1993):

$$\mathrm{e}0 = \mathrm{m}S\mathrm{m}P\mathrm{m}T \tag{a}$$

$$\mathrm{e}S = \mathrm{p}S\mathrm{m}P\mathrm{m}T - \mathrm{m}S\mathrm{m}P\mathrm{m}T \tag{b}$$

$$\mathrm{e}P = \mathrm{m}S\mathrm{p}P\mathrm{m}T - \mathrm{m}S\mathrm{m}P\mathrm{m}T \tag{c}$$

$$\mathrm{e}T = \mathrm{m}S\mathrm{m}P\mathrm{p}T - \mathrm{m}S\mathrm{m}P\mathrm{m}T \tag{d}$$

$$\mathrm{e}SP = \mathrm{p}S\mathrm{p}P\mathrm{m}T - (\mathrm{p}S\mathrm{m}P\mathrm{m}T + \mathrm{m}S\mathrm{p}P\mathrm{m}T) + \mathrm{m}S\mathrm{m}P\mathrm{m}T \tag{e}$$

$$\mathrm{e}ST = \mathrm{p}S\mathrm{m}P\mathrm{p}T - (\mathrm{p}S\mathrm{m}P\mathrm{m}T + \mathrm{m}S\mathrm{m}P\mathrm{p}T) + \mathrm{m}S\mathrm{m}P\mathrm{m}T \tag{f}$$

$$\mathrm{e}PT = \mathrm{m}S\mathrm{p}P\mathrm{p}T - (\mathrm{m}S\mathrm{p}P\mathrm{m}T + \mathrm{m}S\mathrm{m}P\mathrm{p}T) + \mathrm{m}S\mathrm{m}P\mathrm{m}T \tag{g}$$

$$\mathrm{e}SPT = \mathrm{p}S\mathrm{p}P\mathrm{p}T - (\mathrm{p}S\mathrm{p}P\mathrm{m}T + \mathrm{p}S\mathrm{m}P\mathrm{p}T + \mathrm{m}S\mathrm{p}P\mathrm{p}T) + (\mathrm{p}S\mathrm{m}P\mathrm{m}T + \mathrm{m}S\mathrm{p}P\mathrm{m}T + \mathrm{m}S\mathrm{m}P\mathrm{p}T) - \mathrm{m}S\mathrm{m}P\mathrm{m}T \tag{h}$$

As provided in Table 1, the terms on the right-hand side of the equation are plus (p) and minus (m) changes in the control values of S, P and T. The terms on the left-hand side of the equation are as follows: e0 is background effect or the model results, with the least of the S, P, T settings being used in estimating the interactions as additional magnitudes of the various effects are added; e*S*, e*P* and e*T* are individual contributions or the direct effect of the variable; e*SP*, e*ST*, and e*PT* are interactions between two variables; e*SPT* is triple interaction due to incremental changes in S, P, and T. The "e" in the equations represent the effect.

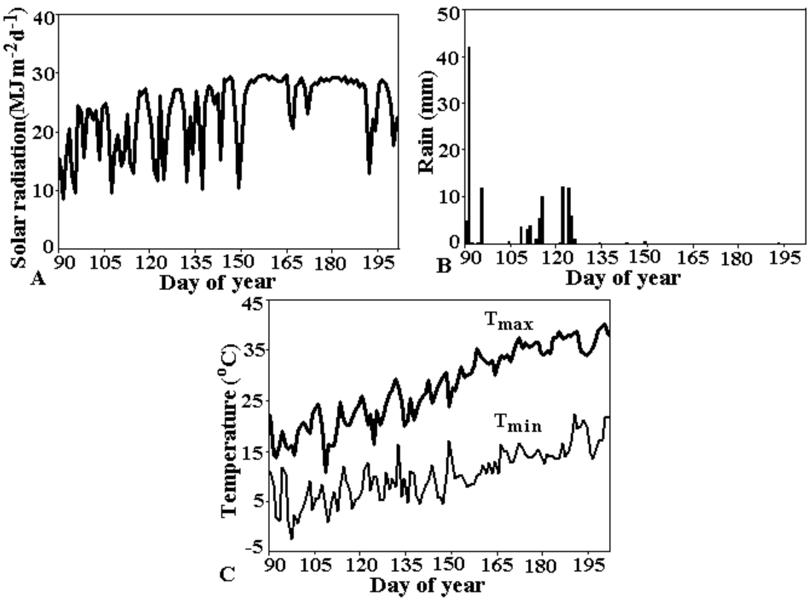

Figure 1. Observed solar radiation (A), precipitation (B) and temperature maximum ($T_{max}$) and minimum ($T_{min}$) (C) for growing period of chickpea (April 1 through July 14).

Table 1. Definition of variables in multiple interaction simulations.

| Treatment | Variable setting | | |
|---|---|---|---|
| | Solar radiation (S) | Precipitation (P) | Temperature (T) |
| m*S*m*P*m*T* | 50% | 50% | -2 |
| p*S*m*P*m*T* | 150% | 50% | -2 |
| mSp*P*m*T* | 50% | 150% | -2 |
| m*S*m*P*p*T* | 50% | 50% | +2 |
| p*S*p*P*m*T* | 150% | 150% | -2 |
| p*S*m*P*p*T* | 150% | 50% | +2 |
| m*S*p*P*p*T* | 50% | 150% | +2 |
| p*S*p*P*p*T* | 150% | 150% | +2 |

The calculated attributes were biomass, harvest index (HI) and evapotranspiration (ET). Some additional attributes including growing period length, FTSW, run-off, transpirational water use efficiency, ratio of transpiration to evaporation, vegetative-stage-biomass (cumulative biomass at R1, say”biomass part A”), reproductive-stage-biomass (cumulative biomass at R8 minus biomass part A, say"biomass part B") and ratio of biomass part B to part A were also calculated for interpreting the response of chickpea to S, P and T.

## Results and discussions

The changes in biomass and HI versus S levels were shown in Figure 2. Generally, the response of biomass to S was higher in irrigated than in rainfed conditions. The S imposed a linear effect on biomass of irrigated-chickpea; the highest value was obtained for 150% of the control, but lowest value for 50%. Other reports for chickpea have also concluded that cloudy weather (which can reduce incident S) (Hernandez, 1986) and artificially diminished light (Verghis et al., 1999) can cause decrease in growth. In rainfed conditions, the biomass showed non-linear response; it was highest for S level that was at 75% of control, and lower when S level increased or decreased; the lowest and second lowest biomass occurred for levels 25 and 150% of control, respectively.

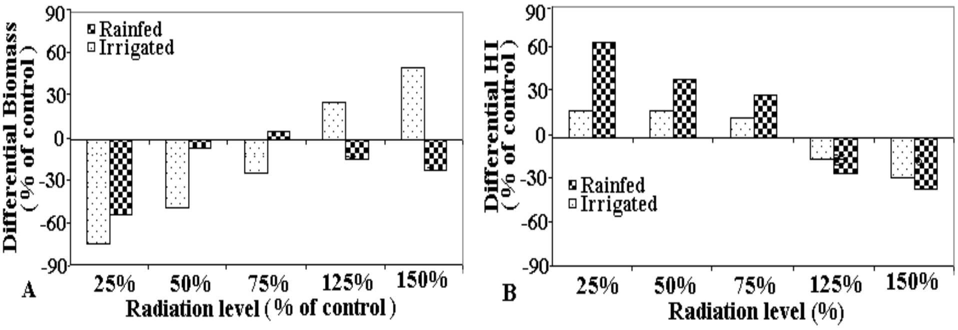

Figure 2. Effects of radiation levels on biomass (A) and harvest index (HI) (B) of rainfed- and irrigated-chickpea. Horizontal line is control.

Despite of biomass, the response of HI to S was higher in rainfed than in irrigated conditions. For rainfed-chickpea, HI inversely changed with changing S; the higher values of HI occurred for lower S levels, when compared with control, and vice versa. For irrigated-chickpea, the values of HI were nearly similar for S levels 25 and 50%, then, like rainfed-chickpea, showed decreasing trend, as S level increased.

The effects of tested S levels on ET for different developmental stages of chickpea were presented in Figure 3. In irrigated conditions, the increase in ET with plant development appeared to occur in nearly two distinct phases for S levels below the control, especially level 25%, as: (1) rapid increase in ET for period from E to R1, and (2) little increase from R1 to R8. For control and for S levels above the control it occurred in nearly four distinct phases as: (1) marked increase in ET for period from E to R1, (2) intermediate increase for R1 to R5, (3) rapid increase for R5 to R7, and (4) intermediate increase for R7 to R8. As shown, it was found a strong relation between ET and S; the value of ET was proportionally changed with changing S level; the cumulative ET at R8 ranged from 130 to 650 mm. In rainfed conditions, like that for low S levels in irrigated conditions, the increase in ET with plant development occurred in two phases. It appeared that for S levels lower than control, there is nearly proportional change in ET with changing S level. For other levels, the value of ET was same as control. It was found a similarity between rainfed and irrigated conditions for values of ET which were obtained only for S levels 25 and 50% of control.

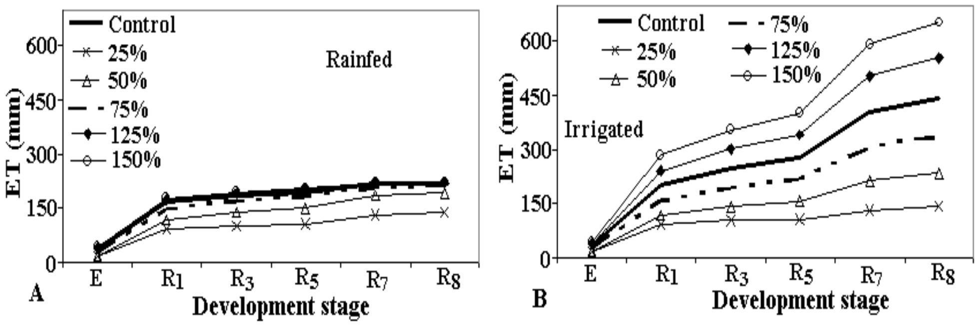

Figure3. Effects of radiation levels on evapotranspiration (ET) in various developmental stages of chickpea under rainfed (A) and irrigated (B) conditions.

In locations with early-growing-period-dominated-rainfall (better saying, winter-dominated-rainfall), like Kermanshah, Iran (see Figure 1B), the factors/treatments which cause higher early growth, and consequently more rapid depletion of soil-stored-moisture, would be resulted in decreased final biomass for rainfed crops, including chickpea, because of experiencing more water stress at reproductive stage. The results indicated that in rainfed conditions, the averaged daily-FTSW over period from E to R1 (and over period from R1 to R8) were equal to 0.87 (0.57), 0.77 (0.26), 0.68 (0.16), 0.61 (0.15), 0.50 (0.14) and 0.46 (0.11) for S levels 25, 50, 75, 100 (control), 125 and 150%, respectively. Additionally, the values of biomass part A (and ratio of biomass part B to part A) were 76 (1.51), 185 (1.32), 262 (0.87), 277 (0.68), 232 (0.69) and 210 gm$^{-2}$ (0.67) for above named S levels, respectively. Based on these values, and on this fact that the leaf area expansion declines when FTSW becomes lower than 0.48 (Soltani et al., 2000), it is cleared that in Kermanshah, Iran, for S level 25%, the rainfed chickpea experiences no water stress in both vegetative and reproductive stages because of very low rate of photosynthesis and growth, and therefore diminished transpiration, and finally decreased depletion of soil-stored-moisture. Then, as S level is enhanced, it proportionally experiences water stress at reproductive stage and even at both stages when S level reaches to 150%. This is confirmed by no increase in ET (i.e. no availability of water) for S levels above the control (Figure 3A). The relatively balanced and consistent growth across both stages, and consequently higher biomass at R8 were obtained for S level 75%. Due to this fact that grain yield is product of biomass and HI, the higher grain yield (53%) was for S level 50% compared to control.

It is generally expected that the biomass for rainfed-chickpea to be higher in situations with more P; but, as shown in Figure4A, it tended to be higher in turn in the 75 and 50% of the control. Based on the values of FTSW which were nearly the same for all P levels, and on those of run-off which were increased with increasing P level, it is concluded that in rainfed conditions of Kermanshah, Iran, no response of biomass to increased P is due to no increase in soil-stored-moisture.

For rainfed chickpea, the value of HI tended to be higher than control, only for P levels 25, 50 and 75% (Figure 4B). For other levels, it was nearly same as control. In rainfed conditions, the values of ET for P levels 25 and 50% were proportionally lower compared to control (Figure 5). There was no difference between P levels 125 and 150% for ET. The values of ET for these levels were slightly higher than control. In irrigated conditions, it was found similar values of ET for P levels 25, 50 and 75%. These values were lower compared to control. The other P levels with similar ET showed relatively higher values, when compared with control.

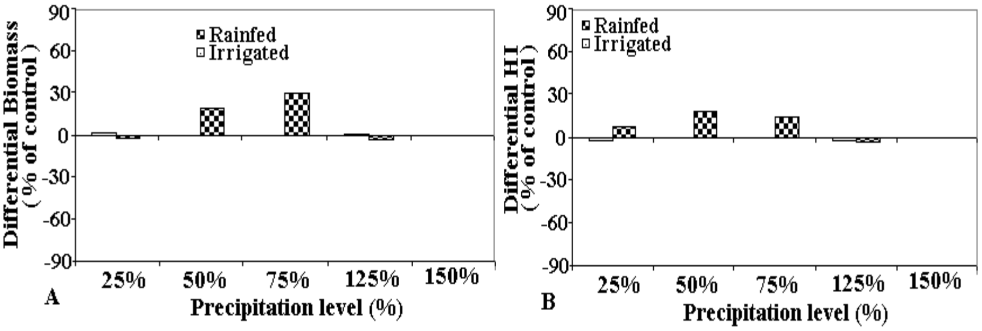

Figure 4. Effects of precipitation levels on biomass (A) and harvest index (HI) (B) of rainfed- and irrigated-chickpea. Horizontal line is control.

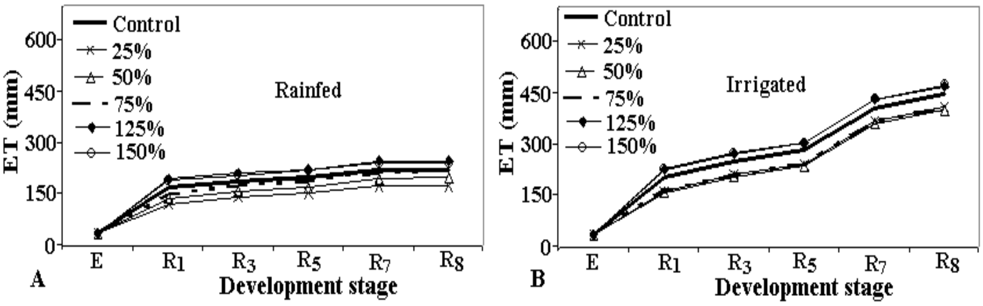

Figure 5. Effects of precipitation levels on evapotranspiration (ET) in various developmental stages of chickpea under rainfed (A) and irrigation (B) conditions.

Overall, like P, T appeared to have relatively smaller impact on biomass and HI, as compared to S (Figure 6); this could be due to the prescribed range (± 2 is only about 10% of control). In irrigated conditions, the biomass found to be relatively lower (4.6%) for 2 $^{o}$C warmer T; part of this may be due to diminished growing period (2%). The effect of other Ts was negligible (0 to 1.6%). In addition to reports of Soltani et al. (2006a), in other reports the high-T-induced decrease in growing period, final biomass and yield for chickpea has been also obtained (e.g. Gan et al., 2004). As shown in Figure7B for irrigated-chickpea, the value of ET was nearly the same for all T levels.

The biomass of rainfed-chickpea was proportionally changed with changing T; it (differential biomass) ranged from -20% (for -2°C) to +19% of the control (for +2 °C). Considering the values of biomass at time 30 days after planting which were 1.62, 3.86, 7.06, 9.67 and 16.18 g $m^{-2}$ for T levels -2, -1, 0 (control), +1 and +2 °C, respectively, it seems that in warmer T runs, the diminishing effects of early-season-low-minimum-temperatures (see Figure 1B) were overcome, and consequently higher growth rate resulted in faster canopy closure, and finally decreased water loss through evaporation (although the value of ET tended to be the same for all T levels (Figure 7A), in both vegetative and reproductive stages the ratio of transpiration to evaporation was higher for warmer, but lower for cooler Ts); this positive effect of warmer T runs was also confirmed by averaged FTSW over vegetative stage, which was equal to 0.57, 0.59, 0.61, 0.61 and 0.63 for above named T levels, respectively; this is in agreement with report of Soltani and Galeshi (2002) for spring wheat. It has been reported that faster growth in early season, when VPD is low, would be resulted in increased $CO_2$ fixation per unit transpirational water loss (Condon et al., 1993; Tanner and Sinclair, 1983). In our evaluation, the value of water use efficiency (ratio of biomass to transpirational water loss) for stages 30 days after planting, R1 and R8 was also higher for warmer, but lower for cooler Ts. Considering the value of growing period length which was about 2.4% shorter for warmer T, it would be concluded that part of increase in biomass for warmer T runs may be due to escape from end-growing-period-occurring drought.

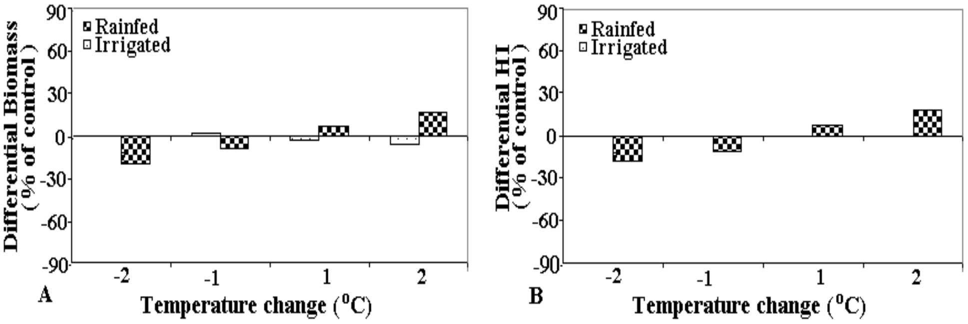

Figure 6. Effects of temperature change on biomass (A) and harvest index (HI) (B) of rainfed- and irrigated-chickpea. Horizontal line is control.

In rainfed conditions, the pattern of change in HI for tested T levels was similar to that of change in biomass. In other conditions, it was not impacted by T.

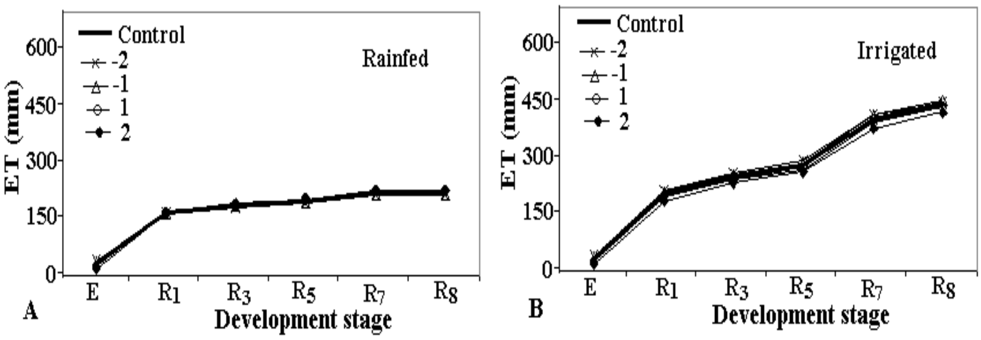

Figure 7. Effects of temperature change on evapotranspiration (ET) in various developmental stages of chickpea under rainfed (A) and irrigation (B) conditions.

The change in biomass and HI versus simultaneously variable changes was presented in Figure8. The biomass for rainfed-chickpea found to be higher (11%) than control only for p*S*m*P*p*T* run (i.e. 50% higher S, 50% lower P, and 2$^{o}$C warmer T, as compared to control). Among other runs, the decrease in biomass was more considerable for p*S*p*P*m*T* (56% vs. 4-11%), indicating that high values of S and P can synergistically interact to further decrease the biomass, when T is relatively cooler. In irrigated conditions, biomass above the control was generally obtained for combinations with high S, but below the control for combinations with low S; additionally, the difference between combinations with low S for biomass below the control, and between combinations with high S for biomass above the control was not huge; therefore, S would be considered as a dominant factor. Among combinations with high S, the crop growth (biomass) was slightly higher for p*S*m*P*p*T*, but slightly lower for p*S*p*P*p*T*, suggesting that P can interact with S and T interaction (i.e., there are triple interaction between P, S and T) even for irrigated-chickpea, which generally expected to show no response to P.

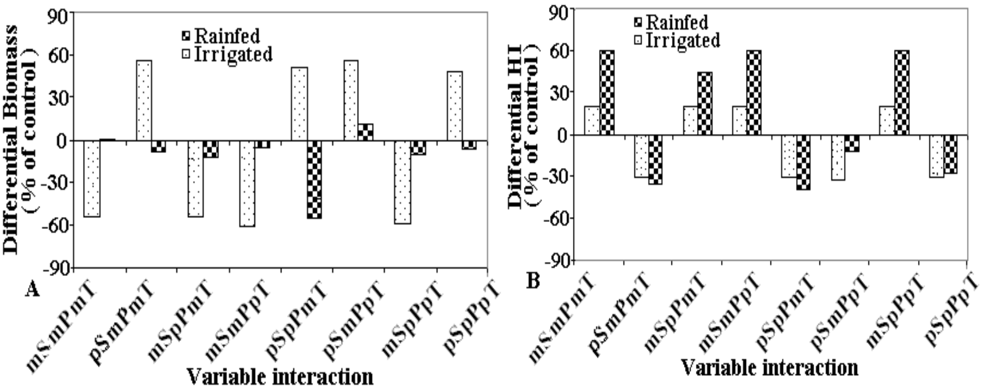

Figure 8. Simulated yield (A) and harvest index (HI) (B) for combinations of plus (p) and minus (m) changes in the control values of solar radiation (S), precipitation (P) and temperature (T). Horizontal line is control.

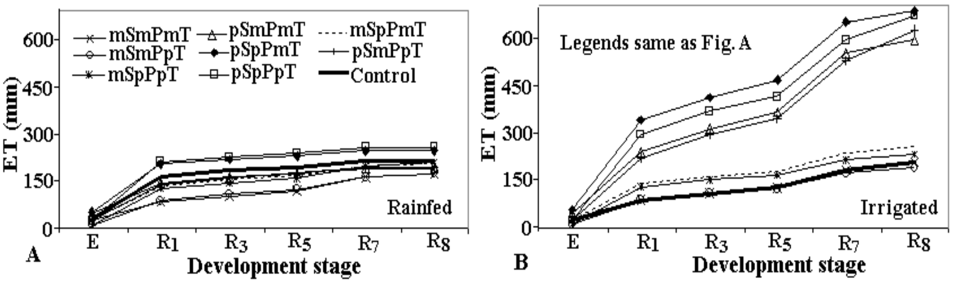

Figure 9. The values of evapotranspiration (ET) in rainfed (A) and irrigated conditions (B) for combinations of plus (p) and minus changes in the control values of solar radiation (S), precipitation (P) and temperature (T).

Again, combinations with increased S appeared to have dominant effect on HI for both rainfed- and irrigated-chickpea; the value of HI was above the control for combinations with low, but below the control for combinations with high S. Among combinations with low S, the increased P (m*S*p*P*m*T*) tended to have relatively lower positive impact on HI for rainfed-chickpea (44% vs. 59-60%). The decrease in HI of rainfed-chickpea for combination with high S and P (p*S*p*P*m*T*) was more considerable than for combination with high S and T (p*S*m*P*p*T*) (40% vs. 12%). For other combinations, it was equal to 28 and 36%. In irrigated conditions, the differential HI was equal to +19% for all combinations with low S, but ranged from -31% to -33% for all combinations with high S.

For rainfed-chickpea, in contrast with control, the higher values of ET was found for combinations with high S, when P (p*S*p*P*m*T*), and when both P and T were above the control (p*S*p*P*p*T*), but lower for low S, when P (m*S*p*P*m*T*), and when T were above the control (m*S*m*P*p*T*) (Figure9). For irrigated-chickpea, the considerable increase in ET was found for combinations with high S, especially when P (p*S*p*P*m*T*), and when both P and T were high (p*S*p*P*p*T*). On the other hand, the values of ET were equal and/or little above the control for combinations with low S.

In Figure 10 (i.e. factor separation plots for biomass and HI) the following information, as defined in materials & methods section, was included: (a) direct effect of individual variable changes, given as e*S*, e*P* and e*T*; (b) the effect of interactions between two variables, given as e*ST*, e*PT* and e*ST*; and (c) the triple effect of all variables, given as e*SPT*. The decrease in biomass of rainfed-chickpea was more sensible for e*SP* (-157 g m$^{-2}$), when compared with e*S* (-42 g m$^{-2}$) and e*P* (-61 g m$^{-2}$), suggesting that increased S and P would synergistically impact the biomass. It was found sensible minus differential biomass for e*S* and e*T*, but more sensible plus differential biomass for e*ST*, indicating other type of synergistically interaction between variables. The triple interaction was also sensible; however, this effect was slightly smaller than the S-T interaction (94 vs. 120 g m$^{-2}$); thus, P changes can antagonistically interact with S-T interaction. In irrigated conditions, although the highest biomass was found for e*S*, existence of antagonistically relations resulted in that the effect for double interaction of S and T to be little.

Overall, the response of HI to double and triple interactions of S, P and T, and to their direct effects was higher for rainfed- than for irrigated-chickpea. In irrigated conditions, there was slightly decreased HI for e*ST*, but slightly increased HI for e*SPT*. The e*S* showed highly diminished HI. Others had no impact. In rainfed conditions, although e*P* and e*S* negatively impacted HI, e*SP* contributed towards increased HI. In addition to e*SP*, the differential HI was also positive for e*ST* and e*PT*, but negative for e*SPT*.

The factor separation analysis results for ET were shown in Figure 11. In rainfed conditions, the values of ET for e*S* and e*P* showed relatively marked increase up to stage R1, the plateau state up to R5, and finally levels off. Averaged over developmental stages, relatively higher ET was obtained for e*S* and e*P*. Based on this fact that more P, and increased S potentially produce higher ET for rainfed conditions, it is physically expected that the value of ET to be more for S-P interaction. But, in Kermanshah, it appeared little increase in ET for e*SP*, due to shortage of rainfall period. In evaluation for other crops, the highest ET has been found for e*SP* because of coincidence of rainfall period with growing period (Mera et al., 2006). In energy balance perspective, ET is a component of S for irrigated conditions, and thus S direct effect also showed up as a dominant term for irrigated chickpea. The value of ET for e*P* and e*SP* was nearly the same, indicating that S-P interaction antagonistically affects ET.

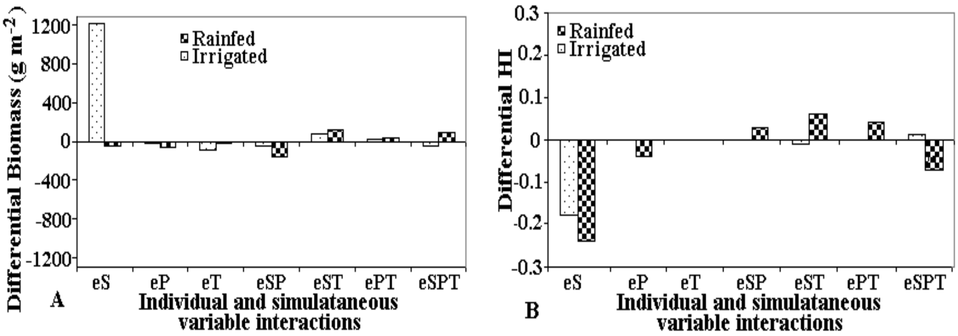

Figure 10. Factor separation plot for chickpea differential yield (A) and differential harvest index (HI) (B) under rainfed and irrigated conditions. The letters S, P, T and e are solar radiation, precipitation, temperature and effect, respectively.

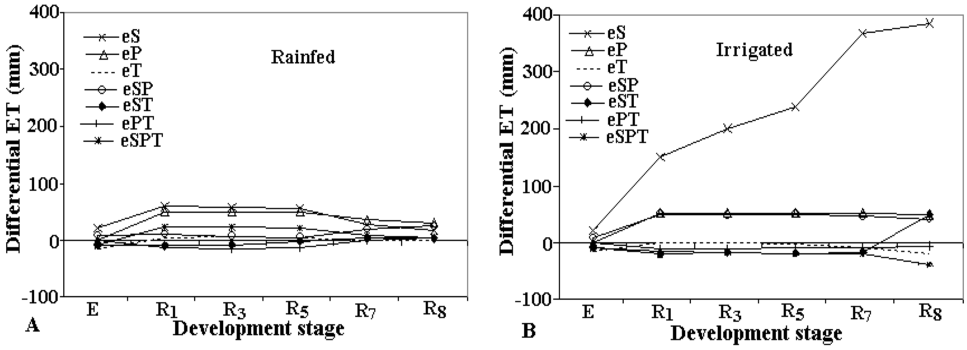

Figure 11. Factor separation plot for differential evapotranspiration (ET) at various developmental stages of rainfed (A) and irrigated (B) chickpea. The letters S, P, T and e are solar radiation, precipitation, temperature and effect, respectively.

## Conclusion

The results revealed that the value of change in attributes was higher for S, compared to P and T. For irrigated-chickpea, the biomass and ET were directly, but HI (nearly) inversely affected by S. T had no impact on HI and ET. The biomass was slightly lower for warmer T. When T, S and P were simultaneously changed, P and T slightly interacted with huge effect of S. For rainfed-chickpea, non-linear response to S was fount for biomass, but linear response for HI. For high S levels, ET was same as control. The decreased levels of P positively affected biomass and HI. There was proportionally change in biomass and HI with changing T. It found various considerable interactions between variables for biomass, HI and ET. For example, among combinations with low S, combination of low S and T, but high P had lower positive effect on HI. When T was cool, high values of S and P synergistically decreased biomass.

It seems that for obtaining more reliably results, these analyses should be done for two or more sowing dates; this suggestion comes from the general expectance for this fact that in arid and semi-arid regions, P could have positive effect on final biomass of rainfed chickpea, but it was not true for this study. In addition, from report of Mera et al. (2006) for meteorological conditions of Clayton, North Carolina, United States (location which, the growing period of crops fully coincides with rainfall season (see their Figure 1)), in which the P has been known as dominant factor for rainfed conditions. In Iran, earlier sowing (dormant seeding) of chickpea, which is achievable and was known as preferred strategy for increasing yield in rainfed conditions (Gholipoor and Soltani, 2005b; Gholipoor et al., 2006a), provides more coincidence of growing period with rainfall season, and therefore, in simultaneously changing the variables, P may interact with S and T interaction, differently from that we obtained.

Generally, the interaction-based results which obtained here demonstrate how the multiple factors of S, P and T, when altered, can interact with each other in order to either reduce or enhance the growth and physiological response of chickpea. In fact, they show multiple vulnerability and sensitivities compared with single variable studies, and therefore, could have important implications for the accurate assessment of crop response to climate change, and finally, for identifying appropriate management practices and genotype characteristics for future climate. Accordingly, results from these studies would benefit from reconsideration in light of other concurrent climate change phenomena and should be adapted as just one possible scenario of a multi-parameter sensitivity analysis.

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