

Evaluating the Response of Rainfed-Chickpea to Population Density in Iran, Using Simulation

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Abstract—The response of growth and yield of rainfed-chickpea to population density should be evaluated based on long-term experiments to include the climate variability. This is achievable just by simulation. In this simulation study, this evaluation was done by running the CYRUS model for long-term daily weather data of five locations in Iran. The tested population densities were 7 to 59 (with interval of 2) stands per square meter. Various functions, including quadratic, segmented, beta, broken linear, and dent-like functions, were tested. Considering root mean square of deviations and linear regression statistics [intercept (a), slope (b), and correlation coefficient (r)] for predicted versus observed variables, the quadratic and broken linear functions appeared to be appropriate for describing the changes in biomass and grain yield, and in harvest index, respectively. Results indicated that in all locations, grain yield tends to show increasing trend with crowding the population, but subsequently decreases. This was also true for biomass in five locations. The harvest index appeared to have plateau state across low population densities, but decreasing trend with more increasing density. The turning point (optimum population density) for grain yield was 30.68 stands per square meter in Isfahan, 30.54 in Shiraz, 31.47 in Kermanshah, 34.85 in Tabriz, and 32.00 in Mashhad. The optimum population density for biomass ranged from 24.6 (in Tabriz) to 35.3 stands per square meter (Mashhad). For harvest index it varied between 35.87 and 40.12 stands per square meter.

Keywords—Rainfed-chickpea, biomass, harvest index, grain yield, simulation.

I. INTRODUCTION

DRY farming is the profitable production of useful crops, without irrigation, on lands that receive annually a rainfall of 20 inches or less. In regions with winter (non-growing season)-dominant rainfall, like Iran, the soil-stored water across the winter tends to be considerably lost at sowing date of spring crops like chickpea. This is due to deep plowing the soil by moldboard plow in conventional agriculture, and consequently more exposure of more moistened soil of lower horizons to sun radiation and wind. Therefore in such situations, the reproductive growth of rainfed-chickpea mainly depends on soil water content (precipitation) across growing period. So, any change of soil water content at growing period and especially at reproductive stage may have a drastic effect on growth and especially grain-filling stage.

One of the important issues in dry farming is population density. When the large quantities of seed employed in humid countries have been sown on dry lands, the result has usually

been an excellent stand early in the season, with a crop splendid in appearance up to early summer. A luxuriant spring crop reduces, however, the water content of the soil so greatly that when the heat of the summer arrives, there is not sufficient water left in the soil to support the final development and ripening. A thick stand in early spring is no assurance to the dry-farmer of a good harvest. The quantity of seed sown depends on many factors, including the value of precipitation across the growing period and its distribution, soil fertility and amount of soil-stored water.

Unfortunately, the amount of precipitation tends to vary considerably across the years. Additionally, some reports indicate the declining trend in precipitation during past decades. For example, an analysis of rainfall data since 1910 by Haylock and Nicholls [10] reveals a large decrease in total precipitation and related rain days in southwestern Australia. In Birjand, Iran, precipitation in April, has had a downwardly trend during past decades [34]. Over the last 50 years, there has been a slight decrease in annual precipitation over China [36], which is supported by a significant (5% confidence level) decrease in the number of rainy days (3.9% per decade). There have been marked decreases in precipitation in the latter part of the 20th century over southern Europe [20]. Since 1976, decreases in precipitation have occurred in South Pacific Convergence Zone [19]. There have also been significant decreases in rain days since 1961 throughout Southeast Asia and the western and central South Pacific [14]. Hulme [11] found significant decreases in precipitation being observed since the late 1970s. Using wavelet-based principal component analysis, Mwale et al. [16] found that East Africa suffered a consistent decrease in the September–October–November rainfall from 1962 to 1997, resulting in 12 droughts between 1965 and 1997. Dore and Lamarche [4] find evidence of a dramatic decline in precipitation in the Sahel, enough to characterize it as a ‘structural break’.

Based on above issues, it can be concluded that the response of growth and yield of rainfed-chickpea to population density should be evaluated based on long-term experiments to include the climate variability. This is achievable just by simulation. In this simulation study, it was aimed to investigate the effect of different population densities on biomass, harvest index, and grain yield of rainfed-chickpea, using CYRUS model.

II. MATERIALS AND METHODS

A. Model Description

In this study, the CYRUS model was recoded in Qbasic programming language, and run to investigate the probable changes in growth and yield of rainfed-chickpea across the different population densities. This model was initially designed in 1999 by Soltani et al. [22]. Then it was developed for seedling emergence [31], for leaf expansion and senescence [30], for response of leaf expansion and transpiration to soil water deficit [23], for response to photoperiod [24], for harvest index [25], for phenological development [28], for nitrogen accumulation and partitioning [29], and for the effect of temperature and CO₂ [33]. The CYRUS has been used for evaluating yield of chickpea and its stability in dormant seeding [32], determining optimum phenology of chickpea for now and future [18], potential effects of individual versus simultaneous climate change factors on growth and water use in chickpea [8], evaluating the effect of future climate change on yield of rainfed-chickpea in northwest of Iran [2], comparing relative effects of temperature and photoperiod on development rate of chickpea [6], and optimizing the dormant sowing of chickpea [7]. The soil water balance sub model of this model with some little modifications has been applied for comparative evaluating the climate-related runoff production in sloped farms of Iran [9], and to study the effect of past climate change on runoff in Gorgan, Iran [5].

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 °Cdays) are required from sowing to emergence at a sowing depth of 5 cm. The physiological day's 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.

In leaf sub model, cardinal temperatures for nod 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 includes 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 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 R₁ (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 and CO₂ concentrations. After correction of RUE for temperature and CO₂ concentration, 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.

Many simulation models assume linearity of harvest index increases 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). Despite of these models, 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 [25].

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 m². 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 [1], it accounted for additions from infiltration, and losses from soil evaporation, transpiration and drainage. Infiltration is calculated from daily rainfall less any runoff. Runoff is estimated using the curve number technique [12]. Soil evaporation (Ev.) is calculated using the two-stage model as implemented in spring wheat model developed by Amir and Sinclair [1]. 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 [35], 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 [35] that it to be approximately 0.75 of the difference between saturated vapor pressure calculated from daily maximum and minimum temperatures.

B. Locations and Evaluated Attributes

Five locations with long-term and reliable daily weather data were selected from Iran for this study. The selected

locations were Isfahan (32.67 °N, 51.87 °E and 1600 m asl; weather data set: 1961-2004), Shiraz (29.55 °N, 52.60 °E and 1488 m asl; weather data set: 1961-2004), Kermanshah (34.32 °N, 47.12 °E and 1322 m asl; weather data set: 1961-2004), Tabriz (38.13 °N, 46.28 °E and 1364 m asl; weather data set: 1966-2004), and Mashhad (36.27 °N, 59.63 °E and 990 m asl; weather data set: 1961-2004). The locations in Iran represent a large geographical area and several climatic zones [9]. Mean annual temperature is 16.4 °C for Isfahan, 17.8 °C for Shiraz, 14.4 °C for Kermanshah, 12.6 °C for Tabriz, and 14.3 °C for Mashhad. The annual rainfall occurs during 35 wet days for Isfahan, 42 for Shiraz, 74 for Kermanshah, 81 for Tabriz, and 63 for Mashhad. The cultivars were Arman for Isfahan and Shiraz, Beauvanij for Kermanshah, Jam for Tabriz, and Hashem for Mashhad [24].

The calculated attributes were biomass, harvest index and grain yield over population densities 7 to 59 (with interval of 2) stands per square meter. The following equations were tested for describing the changes in value of Y (dependent variables: biomass, harvest index and grain yield) across the different densities:

• Quadratic function

$$Y = a + (b \times D) + (c \times D^2) \quad (1)$$

Where a, b and c are parameters of function, and D is density.

• Non-linear function, say “broken linear function”

$$Y = a + b \times D \quad \text{if } D < D_{pp} \quad (2)$$

$$Y = a + b \times D_{pp} \quad \text{if } D \geq D_{pp}$$

$$Y = a + b \times D \quad \text{if } D \geq D_{pp} \quad (3)$$

$$Y = a + b \times D_{pp} \quad \text{if } D < D_{pp}$$

Where a, and b are parameters of function, and D_{pp} is a density at which the value of Y starts to show plateau state (for equation 2), and/or the plateau state ends (for equation 3). The shape of these functions could be seen as thick line in Figs. 2 and 3. In addition to these functions, the following functions were also tested:

$$Y = Y_{\max} \times f(D) \quad (4)$$

Where Y_{\max} is the highest value of Y, and f(D) is density function. In this study, three functions [i.e. f(D)] were selected due to their simplicity as follows:

• Segmented function

$$f(D) = \frac{(D - D_b)}{(D_p - D_b)} \quad \text{if } D_b < D \leq D_p$$

$$f(D) = \frac{(D_c - D)}{(D_c - D_p)} \quad \text{if } D_p < D < D_c \quad (5)$$

$$f(D) = 0 \quad \text{if } D_c \leq D \leq D_b$$

• Beta function

$$f(D) = \left[\left(\frac{D - D_b}{D_p - D_b} \times \frac{D_c - D}{D_c - D_p} \right) \left(\frac{D - D_p}{D_p - D_b} \right) \right]^\alpha \quad (6)$$

if $D_b < D < D_c$

$$f(D) = 0 \quad \text{if } D_b \geq D \geq D_c$$

• Dent-like function

$$f(D) = \frac{(D - D_b)}{(D_{p1} - D_b)} \quad \text{if } D_b < D < D_{p1}$$

$$f(D) = \frac{(D_c - D)}{(D_c - D_{p2})} \quad \text{if } D_{p2} < D < D_c \quad (7)$$

$$f(D) = 1 \quad \text{if } D_{p1} \leq D \leq D_{p2}$$

$$f(D) = 0 \quad \text{if } D_c \leq D \leq D_b$$

Where D_b is the lowest planting density, D_p the density at which the value of Y appears to be high, D_{p1} the density at which the value of Y starts to show plateau state, D_{p2} the end of plateau state, D_c the highest density which was tested. The parameters of these functions were calculated using the NLIN procedure of SAS software. The shape of the last three functions was presented in Fig. 1.

III. RESULTS AND DISCUSSIONS

The average values of rainfall for months December, January, February, March, April, and May were presented in Table 1. The values for other months were ignored, due to the fact that they were negligible. Six months sum rainfall was 104.0 mm (87% of annual rainfall) for Isfahan, 306.6 (92%) for Shiraz, 377.4 (81%) for Kermanshah, 200.5 (72%) for Tabriz and 223.1 (87%) for Mashhad. In December, Shiraz had higher percent of annual rainfall, compared to other locations (22%, versus, 9 to 17%); this is also true for January and February; in March, the obtained percents tended to be highest and 2nd highest for Mashhad, and for Kermanshah and Isfahan, respectively; in April it ranged from 8% (Shiraz) to 18% (Tabriz and Mashhad); in May, Tabriz appeared to have highest rainfall percentage (16%), but Shiraz showed lowest value (2%). Generally, for Tabriz, higher rainfalls were nearly obtained in March, April and May, compared to other months; it was true in March and April for Mashhad, in December and January for Shiraz, and in December, January, March and April for Isfahan, and for Kermanshah.

The results regarding root mean square of deviations (RMSD) and linear regression statistics [intercept (a), slope (b), and correlation coefficient (r)] for predicted versus say “observed” biomass of rainfed-chickpea were presented in Table 2. It is obvious that the function which has the lower

RMSD, but higher correlation coefficient, can be preferred; the value of intercept which is more closer to zero, and that of slope which is more closer to one could also be considered as index of more reliability of function for describing the changes in value of dependent variable (here biomass) across the independent variable (here population density). Based on these explanations, the quadratic function (equation 1) appeared to be appropriate for describing the changes in biomass for Isfahan, Shiraz, Kermanshah, and Mashhad. For Tabriz, the non-linear, say "broken linear", function found to be more reliable. It should be mentioned that the basis for selecting an appropriate function for describing the changes in harvest index and grain yield was also RMSD and linear regression statistics (data not shown).

The results regarding biomass versus population density were shown in Fig. 2. The optimum level of population density that results in a maximum biomass could be determined by solving the derivative of quadratic function. For example, the equation for biomass (Y) in Isfahan was as follow:

$$Y = 241.329877 + (15.415450 \times D) - (0.225332 \times D^2)$$

The 1st derivative (Y') of this function is as:

$$Y' = 15.415450 - (2 \times 0.225332 \times D)$$

$$\text{If } Y'=0 \text{ Then } D = \frac{-15.41545}{-2 \times 0.225332} \rightarrow D = 34.20608$$

In another words, in Isfahan, the highest biomass of rainfed-chickpea will be obtainable just for 34.2 stands per square meter. This value could be considered as optimum population density. Based on this procedure, the optimum population density was 34.4 for Shiraz, 34.7 for Kermanshah, and 35.3 for Mashhad. As mentioned previously, the broken linear was appropriate for Tabriz conditions. For this function, D_{pp} (density at which the value of Y starts to show plateau state) could be considered as optimum population density. It tended to be 24.6, which is considerably lower than those for other four locations. The predicted value of biomass for 7 stands per square meter (the lowest studied population density) was 338.197 gram per square meter in Isfahan, 349.091 in Shiraz, 291.666 in Kermanshah, 314.283 in Tabriz, and 354.591 in Mashhad. Over the optimum population density, Mashhad appeared to have the highest value of biomass (558.963 gram per square meter). In contrast with Mashhad, it was about 9.68% lower in Isfahan, 11.33% lower in Shiraz, 9.68% lower in Kermanshah and 8.35% lower in Tabriz. Based on the values of biomass for optimum and low population densities, the rate of increase in biomass with crowding population density found to be 5.95 gram biomass per one unit of population density in Isfahan, 5.23 in Shiraz, 7.61 in Kermanshah, 7.07 in Tabriz, and 7.30 in Mashhad. Across the optimum to highest (59 stands per square meter) population densities, that of change, say that of decrease, was 5.77 in Isfahan, 4.95 in Shiraz, 5.77 in Kermanshah, 0 in Tabriz, and 5.94 in Mashhad, which are lower than those rates. Generally, considerable increase in population density diminished the biomass. This is due the fact that more dense populations tend

to use the soil-stored water so greatly; hence the reproductive growth of chickpea more considerably decreases due to more experiencing the drought. In a previous study, it has been found a non-linear response of biomass to the factors which potentially tend to almost linearly increase the biomass of irrigated-chickpea [9].

In dry farming, the higher harvest index can be index of successfulness of reproductive growth. Because failure in flowering and grain filling negatively affects value of harvest index. This index determine, in some extend, the value of grain yield. The response of harvest index to changes in population density can be seen in Fig. 3. In all locations, the non-linear function (equation 3) appeared to be appropriate for describing the changes in this index across the tested population densities. Considering the D_{pp} values it was revealed that the value of population density after which the harvest index shows decreasing trend with more increasing density is 35.87 stands per square meter in Isfahan, 38.34 in Shiraz, 37.69 in Kermanshah, 38.66 in Tabriz, and 40.12 in Mashhad. Across the population densities lower than these, the harvest index showed no changes and its value appeared to be highest and 2nd highest in Mashhad (29.06%) and Tabriz (27.947%), respectively. It was nearly the same in Isfahan (24.664) and Shiraz 24.293%). For other location it equaled to 25.34%. Based on the slope (i.e. b) of equation, Mashhad was found to have the highest speed of decrease in harvest index with increasing population density (0.43% decrease in harvest index per one unit increase in population density). On the other hand, Isfahan had the lowest speed of decrease (0.26%). For other locations it varied between 0.29% (in Tabriz) and 0.38% (in Kermanshah). For population density 59, the harvest index ranged from 17.071% (for Isfahan) to 21.97% (for Tabriz).

Grain yield is product of biomass and harvest index. In another word, the net changes in biomass and harvest index is reflected in grain yield. Again, quadratic function was suitable for describing the changes in grain yield with changing population density (Fig. 4). In all locations, the grain yield showed increasing trend with crowding the population, but subsequently decreased. Based on calculation of Y', as it was discussed for biomass case, the turning point (optimum population density) was 30.68 stands per square meter in Isfahan, 30.54 in Shiraz, 31.47 in Kermanshah, 34.85 in Tabriz, and 32.00 in Mashhad. At this point, almost the same grain yield (126.02 to 128.50 gram per square meter) was found for Isfahan, Shiraz and Kermanshah; for other locations, i.e. Kermanshah and Tabriz, it was equal to 146.41 and 164.21, respectively. Across the population densities lower than optimum, the highest and 2nd highest rate of change in grain yield was found for Mashhad, and Kermanshah, respectively; for other locations, it ranged from 1.86 to 2.12 gram grain yield per one unit of population density. Across the population densities higher than optimum, the named rate was 2.23, 2.36, 2.79, 1.84, and 2.99 gram grain yield per one unit of population density, for Isfahan, Shiraz, Kermanshah, Tabriz, and Mashhad, respectively.

IV. CONCLUSION

Generally, results indicated that in all locations, grain yield tends to show increasing trend with crowding the population, but subsequently decreases. This was also true for biomass in five locations. The harvest index appeared to have plateau state across low population densities, but decreasing trend with more increasing density. The turning point (optimum population density) for grain yield was 30.68 stands per square meter in Isfahan, 30.54 in Shiraz, 31.47 in Kermanshah, 34.85 in Tabriz, and 32.00 in Mashhad. The optimum population density for biomass ranged from 24.6 (in Tabriz) to 35.3 stands per square meter (Mashhad). For harvest index it varied between 35.87 and 40.12 stands per square meter.

The results of this study may be useful just for conventional agriculture. Because in no-tillage or minimum tillage systems for which the soil water content, and hence the optimum population density, tend to be different from that in mould-board-tilled soil. It is proposed that, the similar simulation study to be also done for crop-residue-covered soil. Because the numerous positive impacts have been attributed to the leaving the crop residue on soil surface, like enhancing yield [Power et al., 1998], soil organic carbon [3], soil nitrogen content [13], C/N ratio [15], and increasing soil water content due to decreased evaporation [17].

TABLE I
MONTHLY RAINFALL (AND PERCENT OF ANNUAL RAINFALL) IN 6 MONTHS
FOR FIVE LOCATIONS OF IRAN

| Month | Location | | | | |
|----------|----------------|----------------|----------------|----------------|----------------|
| | Isfahan | Shiraz | Kermanshah | Tabriz | Mashhad |
| December | 20.1 (17%) | 73.0 (22%) | 68.6 (15%) | 25.9 (9%) | 26.7 (10%) |
| January | 20.0 (17%) | 88.7 (27%) | 67.4 (15%) | 21.7 (8%) | 33.2 (13%) |
| February | 14.4 (12%) | 56.3 (17%) | 60.6 (13%) | 19.9 (7%) | 35.5 (14%) |
| March | 21.5 (18%) | 54.5 (16%) | 84.9 (18%) | 38.8 (14%) | 53.8 (21%) |
| April | 19.4 (16%) | 28.2 (8%) | 65.9 (14%) | 49.8 (18%) | 45.9 (18%) |
| May | 8.6 (7%) | 5.9 (2%) | 30.0 (6%) | 44.4 (16%) | 28.0 (11%) |
| Sum# | 104.0 (87%) | 306.6 (92%) | 377.4 (81%) | 200.5 (72%) | 223.1 (87%) |

#: The portion of six-month cumulated-rainfall to annual rainfall may be negligibly lower and/or higher than percent in parenthesis; because the round (non-decimal) values were just presented.

TABLE II
ROOT MEAN SQUARE OF DEVIATIONS (RMSD; $G M^{-2}$) AND LINEAR
REGRESSION STATISTICS [INTERCEPT (A), SLOPE (B), AND CORRELATION
COEFFICIENT (R)] FOR PREDICTED VS. SAY "OBSERVED" BIOMASS OF
RAINFED-CHICKPEA FOR FIVE LOCATIONS OF IRAN

| Function | Location | RMSD | a | b | r |
|---------------|------------|-------|------------------------------------|----------------------|------|
| | | | \pm S.E. | \pm S.E. | |
| Dent-like | Isfahan | 71.45 | -2.094 \pm 0.196 | 0.408 \pm 0.010 | 0.47 |
| | Shiraz | 67.05 | -3.025 \pm 0.104 | 0.413 \pm 0.026 | 0.49 |
| | Kermanshah | 72.55 | -1.917 \pm 0.207 | 0.551 \pm 0.008 | 0.41 |
| | Tabriz | 49.77 | -2.082 \pm 0.240 | 0.440 \pm 0.008 | 0.33 |
| | Mashhad | 66.54 | -2.220 \pm 0.219 | 0.779 \pm 0.009 | 0.40 |
| Segmented | Isfahan | 89.05 | -2.233 \pm 0.005 | 0.804 \pm 0.011 | 0.30 |
| | Shiraz | 60.00 | -1.987 \pm 0.775 | 0.684 \pm 0.013 | 0.40 |
| | Kermanshah | 70.11 | 2.005 \pm 0.109 | 0.802 \pm 0.009 | 0.48 |
| | Tabriz | 58.22 | 4.515 \pm 0.283 | 1.903 \pm 0.013 | 0.45 |
| | Mashhad | 60.64 | -4.001 \pm 0.140 | 0.806 \pm 0.011 | 0.52 |
| Beta | Isfahan | 51.75 | -2.290 \pm 0.440 | 0.549 \pm 0.010 | 0.39 |
| | Shiraz | 68.36 | -4.000 \pm 0.233 | 0.777 \pm 0.007 | 0.44 |
| | Kermanshah | 77.71 | -3.197 \pm 0.180 | 0.668 \pm 0.007 | 0.33 |
| | Tabriz | 59.02 | -4.106 \pm 0.201 | 0.622 \pm 0.009 | 0.48 |
| | Mashhad | 40.04 | -3.080 \pm 0.190 | 0.984 \pm 0.008 | 0.40 |
| Broken linear | Isfahan | 44.05 | -2.090 \pm 0.400 | 0.469 \pm 0.011 | 0.41 |
| | Shiraz | 60.30 | -4.100 \pm 0.203 | 0.607 \pm 0.006 | 0.40 |
| | Kermanshah | 72.01 | -3.497 ⁱ \pm 0.180 | 0.560 \pm 0.055 | 0.33 |
| | Tabriz | 22.00 | -0.406 \pm 0.001 | 0.972 \pm 0.002 | 0.69 |
| | Mashhad | 55.55 | -2.980 \pm 0.190 | 0.484 \pm 0.005 | 0.51 |
| Quadratic | Isfahan | 30.70 | -0.290 \pm 0.440 | 0.909 \pm 0.001 | 0.66 |
| | Shiraz | 35.06 | 1.000 \pm 0.233 | 0.807 \pm 0.004 | 0.71 |
| | Kermanshah | 37.01 | -1.197 \pm 0.177 | 0.955 \pm 0.003 | 0.65 |
| | Tabriz | 60.72 | -4.888 \pm 0.221 | 0.599 \pm 0.011 | 0.38 |
| | Mashhad | 39.04 | -1.080 \pm 0.190 | 0.933 \pm 0.001 | 0.62 |

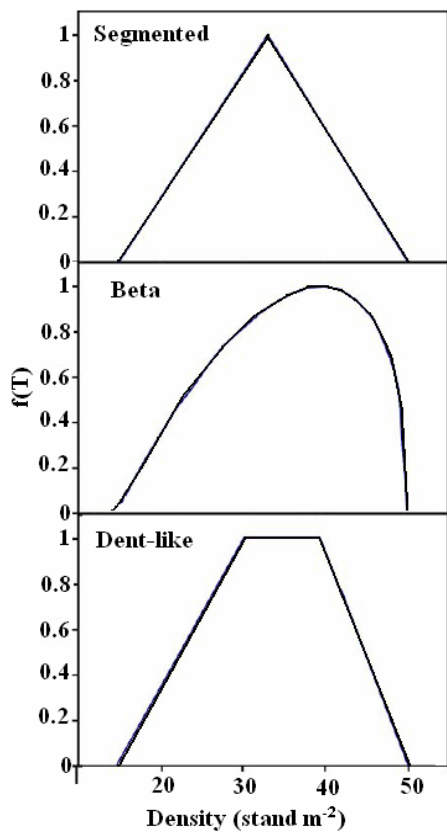


Fig. 1 Functions tested for describing the response of biomass, harvest index and grain yield to population density

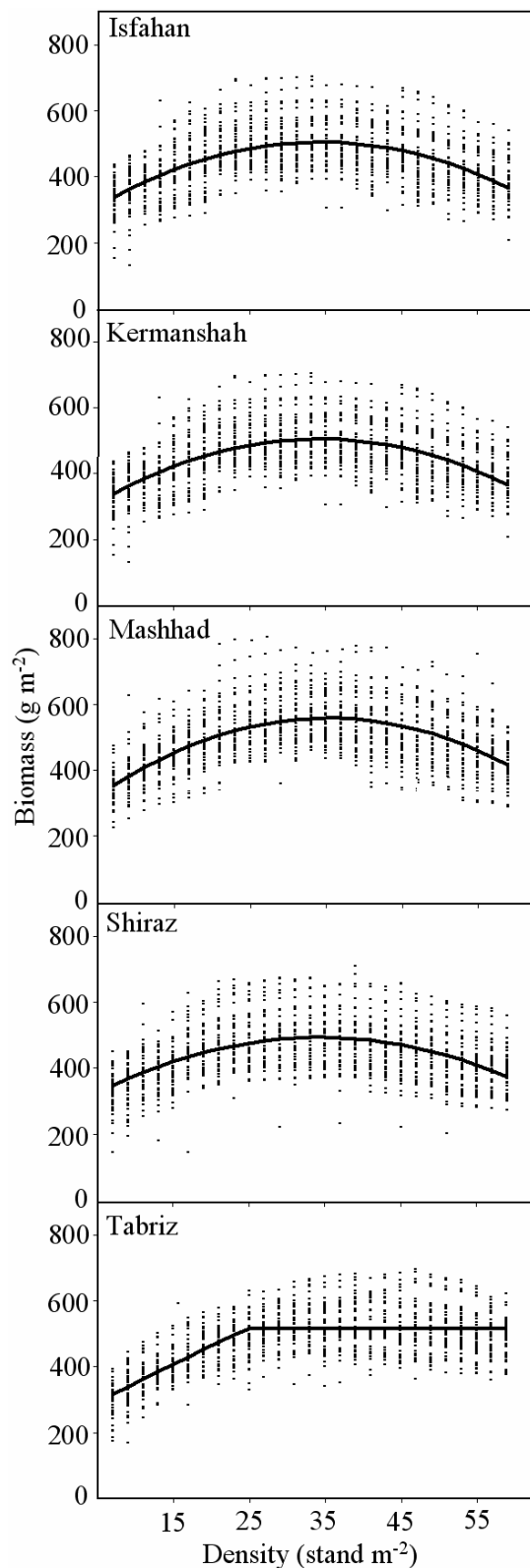


Fig. 2 The changes in biomass of rainfed-chickpea across the tested population densities in five locations of Iran

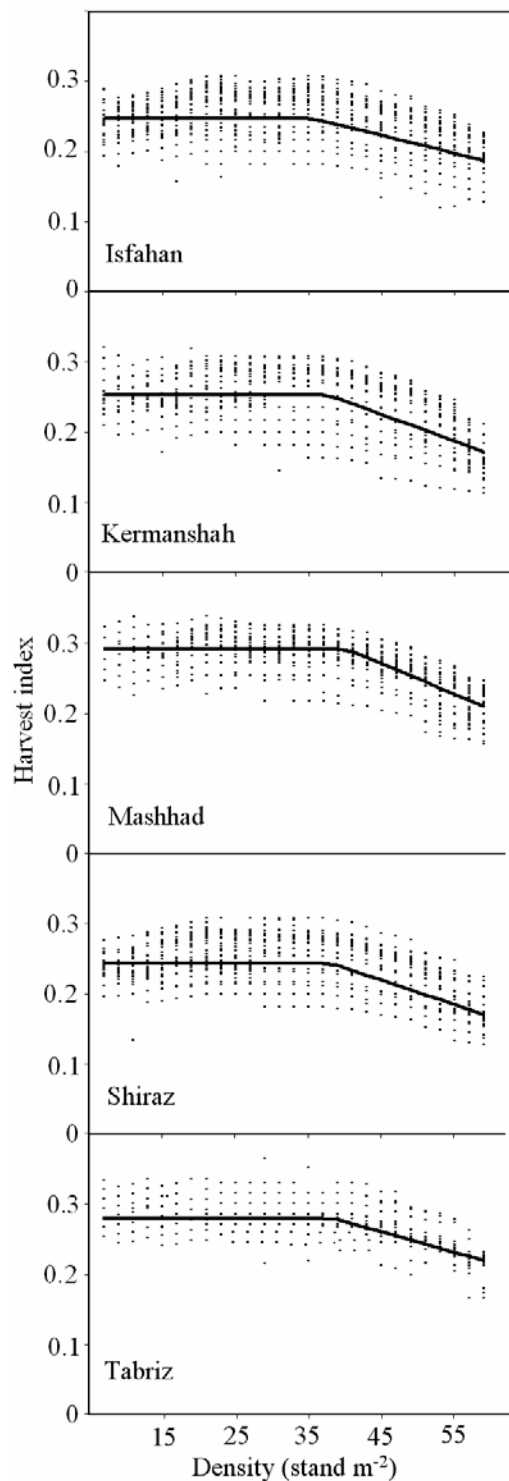


Fig. 3 The changes in harvest index of rainfed-chickpea across the tested population densities in five locations of Iran

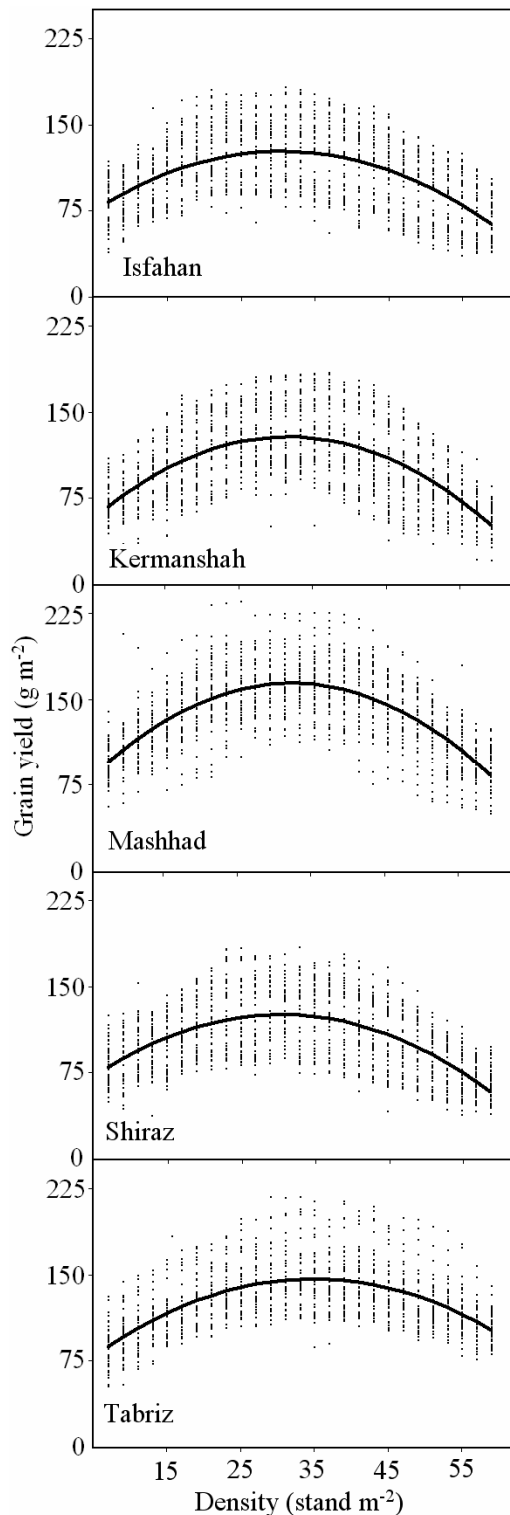


Fig. 4 The changes in grain yield of rainfed-chickpea across the tested population densities in five locations of Iran

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