International Journal of Disaster Risk Reduction 13 (2015) 37–51

Contents lists available at ScienceDirect

International Journal of Disaster Risk Reduction

journal homepage: www.elsevier.com/locate/ijdrr

Vulnerability assessment of wheat and maize production affected by drought and climate change

Sarvenaz Farhangfar, Mohammad Bannayan*, Hamid Reza Khazaei, Mohammad Mousavi Baygi

Faculty of Agriculture, Ferdowsi University of Mashhad, PO Box 91775, 1163 Mashhad, Iran

ARTICLE INFO

Article history:
Received 9 January 2015
Received in revised form
7 March 2015
Accepted 9 March 2015
Available online 26 March 2015

Keywords:
Agricultural vulnerability
Climate change
Drought

ABSTRACT

Agricultural vulnerability can be referred to the degree that agricultural systems may experience harm due to a stress. A simulation study was conducted to assess the vulnerability of wheat (irrigated and rainfed) and maize production due to drought and climate change in the Northeast of Iran. UNEP Aridity Index (AI_U) was calculated to measure drought situation in five agricultural centers including Birjand, Bojnourd, Mashhad, Sabzevar and Torbat Heydarieh. Projected changes in climate variables were simulated by two General Circulation Models: HadCM3 and IPCM4 under three scenarios (A1B, A2 and B1), simulated by LARS-WG. The Cropping System Model (CSM)-CERES-Wheat and (CSM)-CERES-Maize were used for crop growth simulation under projected climate conditions. In order to quantify the magnitude of vulnerability to varying drought conditions, vulnerability was considered as a function of sensitivity, well-being state relative to its damage threshold and exposure. Vulnerability was calculated considering severe droughts in the selected years and the expected vulnerability considering the expected frequency of drought. The results showed that in all the study locations the wheat and maize production have been affected extremely by severe droughts during the base period and both crops were extremely sensitive to drought. It was also projected that crop production will be extremely vulnerable to probable droughts during the projected years the same as the base period.

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1. Introduction

Vulnerability assessment of agricultural crops is an effective approach to realize the impacts of climate change and extreme climatic events on agricultural systems. Vulnerability definition differs based on subject and study orientation. Vulnerability was defined as the capacity of individuals to respond to, recover from or adapt to livelihood stress as a result of the impacts of such environmental change [1]. It was also considered as the likelihood that an individual to be exposed and adversely affected by a hazard [2]. In recent years vulnerability was generally considered as a function of exposure, sensitivity and adaptive capacity [3–5]. Sensitivity reflects the degree to which a given system responds to the fluctuations in stress, either positively or negatively [3,6]. Adaptive capacity has been defined as the capacity of a system to adjust to the change and take advantage from it [3,7,8]. Exposure is the possibility of the system being exposed to the concerned change in the stress [3,4]. In developing countries, drought vulnerability constitutes a threat to livelihoods, the ability to maintain productive systems, and healthy economics. Drought vulnerability is different for different individuals, regions and nations [9]. Defining a set of indicators [7] is one of the typical methods to

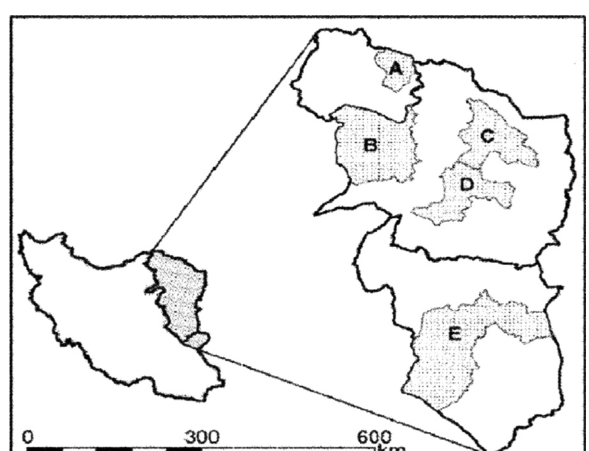

Fig. 1. Geographical study locations (A) Bojnourd, (B) Sabzevar, (C) Mashhad, (D) Torbat Heydarieh, (E) Birjand [45].

* Corresponding author. Fax: +98 511 8787430.
E-mail addresses: banayan@um.ac.ir, mobannayan@yahoo.com (M. Bannayan).

http://dx.doi.org/10.1016/j.ijdrr.2015.03.006
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Table 1
Latitude (Lat), longitude (Long), elevation (Elev), and annual average of climate variables for the study sites in Iran.

site	Lat	Long	Elev (m)	Average Temperature (°C) Min.	Max.	Total precipitation (mm)	Time period
Birjand	32° 52′ N	59° 12′ E	1491	8.2	24.3	165.4	1961–2009
Bojnourd	37° 28′ N	57° 19′ E	1091	6.9	19.6	265	1977–2009
Mashhad	36° 16′ N	59° 38′ E	999	8.3	21.6	256.5	1961–2009
Sabzevar	36° 12′ N	57° 43′ E	977	11.8	24.7	197.8	1961–2009
Torbat Heydariyeh	35° 16′ N	59° 13′ E	1450	7.5	20.4	276.6	1961–2009

Table 2
Calculated genetic coefficients of Sardari cultivar (Rainfed wheat) [40] and three cultivars of irrigated wheat [52].

Cultivar	P1V	P1D	P5	G1	G2	G3	PHINT
Sardari	1	40	450	13	41	1.5	60
Roshan	8	58	620	16	34	1.1	87
Falat	5	60	650	18	38	1.2	87
Ghods	3	54	600	15	32	1.1	89

P1V: Days at optimum vernalizing temperature required to complete vernalization, P1D: Percentage reduction in development rate in a photoperiod 10h shorter than the threshold relative to that at the threshold, P5: Grain filling (excluding lag) phase duration (°C.d), G1: Kernel number per unit canopy weight at anthesis, G2: Standard kernel size under optimum conditions (mg), G3: Standard, non-stressed dry weight (total, including grain) of a single tiller at maturity (g), PHINT: Interval between successive leaf tip appearances (°C.d).

quantify vulnerability, which was used in the present study. In this method the agricultural system is considered as the hazard affected body and a series of vulnerability indicators are constructed. Many researchers have studied vulnerability considering different approaches such as [4,7,10–15]. Vulnerability and adaptation of rainfed agriculture to climate change and variability in semi-arid condition of Tanzania was studied and the vulnerability of rainfed agriculture to the effects of climate change was reported [16]. The vulnerability of rainfed maize in southern Malawi was evaluated and showed that the drought conditions in February and early March lead to most damage to maize yields in this region [17]. The study on vulnerability of crops to drought in Ghana using rainfall, yield and socio-economic data showed that the vulnerability of crop production to drought has discernible geographical and socioeconomic patterns, with the northern, upper west and upper east regions being the most vulnerable [18]. Evaluation of climate change, vulnerability and adaptation in the North Africa especially in Morocco showed that climate change will likely have the strongest effect on Morocco where the agricultural sector is of high importance for the country's economy and particularly for poor people [19].

Table 3
Calculated genetic coefficients of maize cultivar ‘Single Cross 704’ [53].

P1	P2	P5	G2	G3	PHINT
250	0.1	600	700	17	30

P1: Thermal time from seedling emergence to the end of the juvenile phase expressed in degree days above a base temperature of 8 °C during which the plant is not responsive to changes in photoperiod, P2: Extent to which development (expressed as days) is delayed for each hour increase in photoperiod above the longest photoperiod at which development proceeds at a maximum rate (which is considered to be 12.5 h), P5: Thermal time from silking to physiological maturity (expressed in degree days above a base temperature of °C. d), G2: Maximum possible number of kernels per plant, G3: Kernel filling rate during the linear grain filling stage and under optimum conditions (mg day^{-1}), PHINT: Phylochron interval; the interval in thermal time (degree days) between successive leaf tip appearances.

Table 4
The classes of aridity index used in this study.

UNEP	Climate class
$AI_U \leq 0.05$	Hyper-arid
$0.05 < AI_U < 0.2$	Arid
$0.2 < AI_U < 0.5$	Semi-arid
$0.5 < AI_U < 0.65$	Sub-humid
$AI_U \geq 0.65$	Humid

Table 5
The classes of SEN, V_{EXPS}, V_{EXPL}, EV_{EXP}, T_{EXP} and EEXP [41].

EEXP		V_{EXPL}, V_{EXPS} and EV_{EXP}		SEN	
0–1	Low	< 5	Low	< 50	Low
1–1.5	Slight	5–10	Slight	50–100	Slight
1.5–2	Moderate	10–15	Moderate	100–150	Moderate
2–2.5	High	15–20	High	150–200	High
> 2.5	Extremely high	> 20	Extremely high	> 200	Extremely high

Table 6
Comparison of simulated and observed minimum and maximum temperatures (T_{min} and T_{max}) and precipitation simulated by LARS-WG by Root Mean-squared Error (RMSE), Root Mean Deviation (RMD) and R^2 values during the base period.

Station	Parameters	RMSE	RMD	R^2
Birjand	T_{min}	2.52	0.56	0.90
	T_{max}	1.33	0.41	0.58
	Precipitation	5.16	9.40	0.96
Bojnourd	T_{min}	2.91	0.57	0.83
	T_{max}	2.43	1.16	0.92
	Precipitation	6.80	9.93	0.60
Mashhad	T_{min}	2.41	0.57	0.89
	T_{max}	1.71	0.61	0.74
	Precipitation	3.43	9.71	0.93
Sabzevar	T_{min}	1.46	0.24	0.48
	T_{max}	1.26	0.38	0.78
	Precipitation	6.34	6.98	0.96
Torbat Heydarieh	T_{min}	2.72	0.74	0.96
	T_{max}	1.16	0.28	0.75
	Precipitation	6.38	8.50	0.96

Climate change and its potential effects on frequency and severity of extreme climatic events like drought is a concerning matter. Climate change has a profound influence on crop production sustainability in arid and semi-arid environments [20]. A more arid climate is usually accompanied by an increase in the frequency and severity of droughts [21]. An increasing trend of drought has been indicated by several studies in various locations such as the Mediterranean region [22,23], eastern China [24], United Kingdom [25,26], Italy [27] and Iran [28,29]. On the other hand a decreasing trend of crop production under climate change is indicated by several studies, such as [30–32] which evaluated climate change impacts on maize production, [33] Maize and wheat, [34] soybean; [35] cotton and [36] peanut. Drought prevention and mitigation has become the important steps of promoting economic and social sustainable development [37].

Table 7
Comparison of simulated and observed grain and biological yield and maximum leaf area index by Root Mean-squared Error (RMSE), Root Mean Deviation (RMD), Model Efficiency (EF) and R^2 values.

Crop	Parameters	RMSE	RMD	EF	R^2
Sardari	Grain yield	5.11	4.1	0.1	0.80
	Biological yield	4.7	4.2	−4.1	0.50
	Maximum leaf area index	7.8	6.7	0.13	0.92
Roshan	Grain yield	5.2	4	0.2	0.77
	Biological yield	4.5	4.1	−3.9	0.51
	Maximum leaf area index	7.5	6.5	0.15	0.89
Falat	Grain yield	5.3	4.3	0.3	0.75
	Biological yield	4.4	4.4	−4	0.49
	Maximum leaf area index	7.7	6.9	0.12	0.88
Ghods	Grain yield	5.4	3.9	0.3	0.81
	Biological yield	4.6	4.1	−3.8	0.52
	Maximum leaf area index	7.6	6.6	0.11	0.84
Single Cross 704	Grain yield	8.90	−0.20	−0.90	0.85
	Biological yield	6.90	0.60	0.50	0.75
	Maximum leaf area index	12.70	10.50	0.60	0.92

Cereals are overwhelmingly the major source of food supplies for direct human consumption. The geographical concentration of major grain supplies against the geographical dispersion of demand suggests that trade of cereals will continue to be important in fulfilling grain requirements, particularly for wheat and maize. Reports have showed that there are 7.05 and 0.42 million ha under wheat and maize cultivation in Iran with the average yield of 1.98 t/ha and 5.97 t/ha respectively [38]. The arid and semi-arid climate in most parts of Iran is associated with long dry summer and winter rainfall [39] which makes its semi-arid Mediterranean environment vulnerable to potential future climate change impacts [40]. As a multi-faceted biophysical and socio-economic system, the agricultural system is heavily affected by variation and change in climate conditions. Extreme climatic events such as severe drought can often cause devastating damage to agriculture and consequently to rural communities [41]. This signifies any study on the vulnerability of agricultural crops to drought in order to mitigate any loss and guarantee the national food security. The objective of this study is to investigate the relationship between wheat and maize production and occurrence of meteorological droughts over time, and consequently to examine how sensitive and vulnerable wheat and maize production are to varying

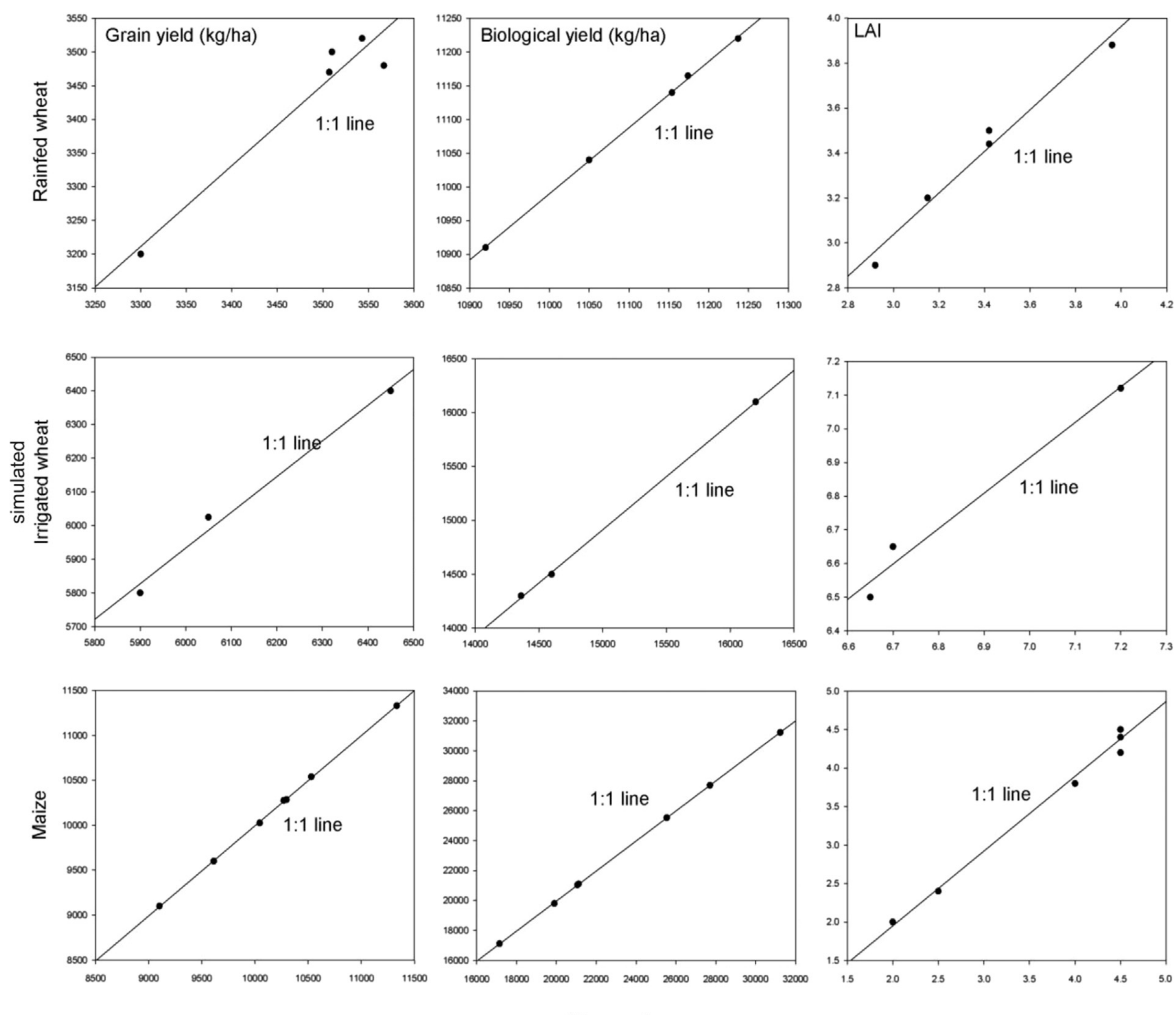

Fig. 2. Comparison of simulated and observed LAI, grain yield and biological yield for irrigated and rainfed wheat and maize.

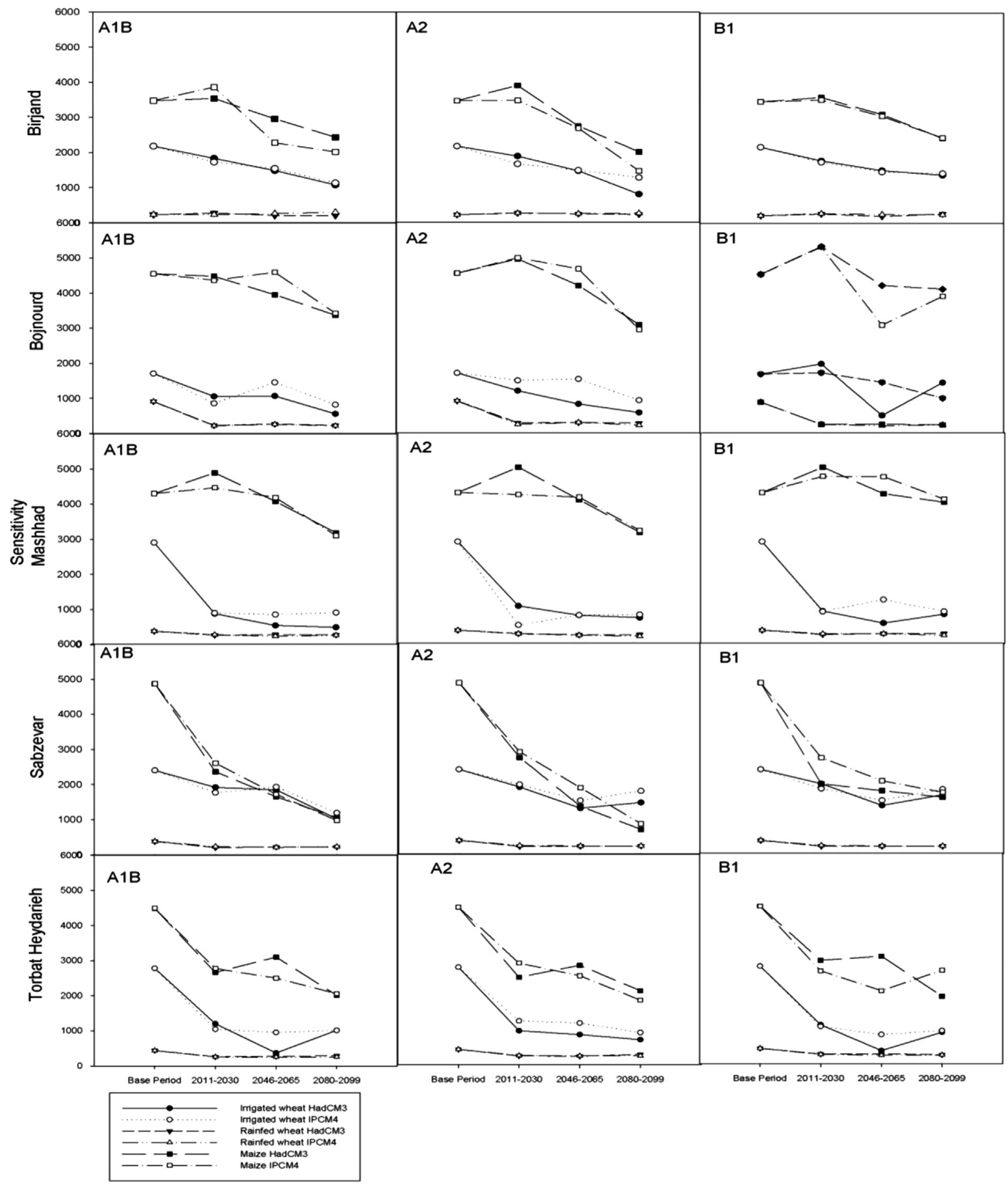

Fig. 3. Estimated values of sensitivity in the growing season in the study locations during the base period and the projected years.

drought conditions in the northeast of Iran using the farm reported and model simulated yields.

2. Materials and methods

2.1. Study area

This study is concerned with wheat and maize production in the northeast of Iran and lies between 38° S and 30° N latitude and 55° W and 61° E longitude, including Northern Khorasan, Khorasan Razavi and Southern Khorasan provinces. The region is mountainous in the north while southern part is flat. The climate is generally arid and semi-arid so that the degree of dryness increases southward [42]. Cereals are the major crops in these areas and they are among the top cereal producers among the other provinces [39]. According to the Khorasan Jihad-Agriculture Organization, in 2011 Khorasan Razavi had the third most harvested area of about 7% and the third most production of about 6.8%, in the country [43]. Five study locations are the dominant agricultural regions in this area including Birjand, Bojnourd, Mashhad, Sabzevar and Torbat Heydarieh (Fig. 1). The physiographic details of the study locations are presented in Table 1. Average precipitation across the area during the last 40 years was 222 mm and

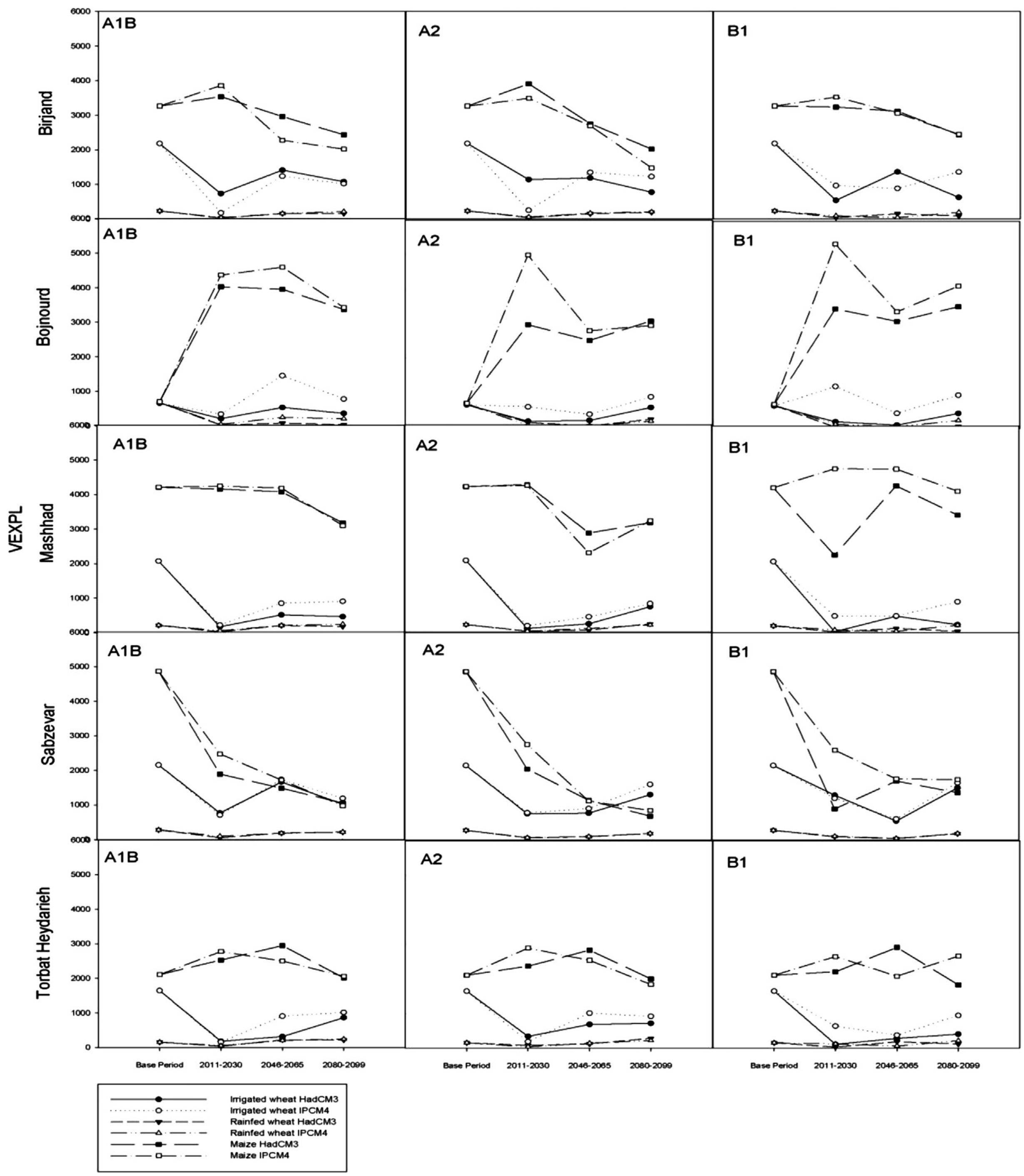

Fig. 4. Estimated values of V_{EXPL} in the growing season in the study locations during the base period and the projected years.

varies from about 169 mm at the southern area (Birjand) to 269 mm in northern areas (Bojnourd) [44].

2.2. Weather data

Historical daily maximum and minimum air temperature (°C), precipitation (mm) and solar radiation (MJ m^{-2} d^{-1}) for the period of 1961–2008 were collected for each study location from their established climatologic stations. Climatic data for Bojnourd station was available only from 1977 to 2008 (Table 1). Considering the required base period data for general circulation models (GCMs) (1970–2000) daily climatic data including minimum and maximum temperature and precipitation were simulated for this station using Weather Generator Program, Weatherman, within DSSAT mechanistic model (Decision Support System for Agrotechnology Transfer) for 7 years (1970–1977).

Two general circulation models (GCM) including IPCM4 and HadCM3, which were developed by Institute Pierre Simon Laplace, France [46] and United Kingdom Met Office Hadley Centre [47], respectively were used in this study. Simulations were under A1B, A2 and B1 emission scenarios. Since daily climatic data are required for the crop simulation model, a stochastic weather generator (LARS-WG) was used to downscale monthly data to daily time series of maximum and minimum temperature, precipitation and solar radiation for future climate during three periods (2011–2030, 2046-2065 and 2080–2099). This weather generator uses

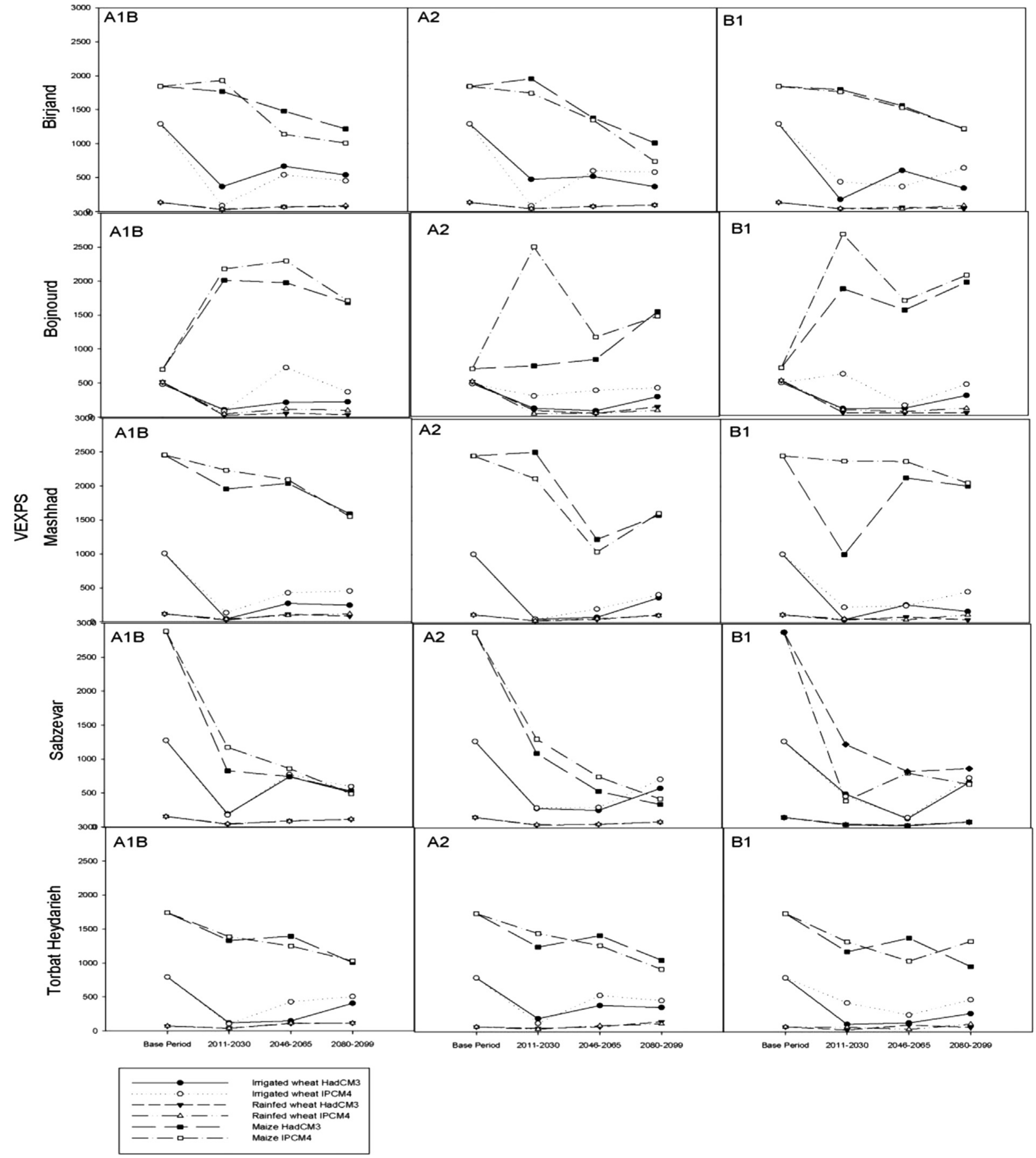

Fig. 5. Estimated values of V_{EXPS} in the growing season in the study locations during the base period and the projected years.

absolute and relative change of climatic variables in comparison with the base period for a given site [48].

In this study four series of data were considered including the base period and the projected years by LARS-WG for 2011–2030, 2046–2065 and 2080–2099. All the analyzes and simulations, analyzing the conditions of drought and vulnerability assessment were applied to all these data.

2.3. Crop data

Historical crop yields at the county level for wheat (irrigated and rainfed) and maize were collected for study locations from the established Ministry of Agricultural. Non-climatic influences such as improvements in crop genetics and technical factors were removed by detrending the time series in yield productions by means of Double Exponential Smoothing [49]. Exponential smoothing assigns exponentially decreasing weights as the observations get older and recent observations are given relatively higher weight than the older observations [39].

2.4. Crop model

In the present study the potential wheat and maize yield was simulated by the Cropping System Model (CSM)-CERES-Wheat and (CSM)-CERES-Maize (DSSAT) version 4.5 for three periods (2011–2030, 2046–2065 and 2080–2099). This model simulates complex management strategies for a wide range of weather and soil conditions and is able to analyze the interactions of these

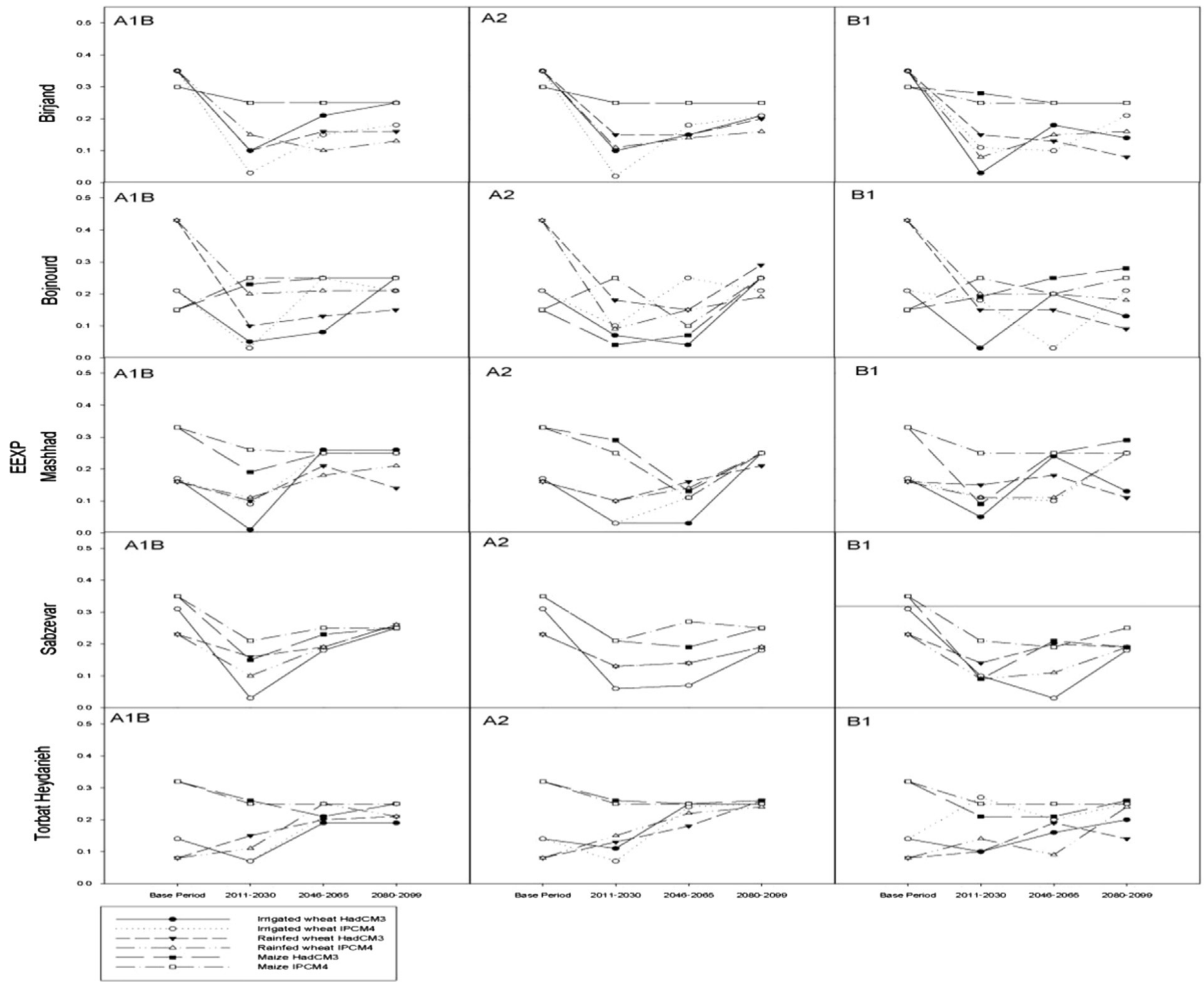

Fig. 6. Estimated values of EEXP in the growing season in the study locations during the base period and the projected years.

strategies with environmental conditions. The model has demonstrated its high reliability under different climates, soil, and management conditions [50] and can simulate the impact of weather, soil water, and soil nitrogen dynamics on growth and yield [51]. The (CSM)-CERES-Wheat model was calibrated based on the calculated genetic coefficients of rainfed wheat cultivar Sardari by [40] for the rainfed wheat and the calculated genetic coefficients of three cultivars of irrigated wheat including Roshan, Falat and Ghods cultivars by [52]. The calculated coefficients for irrigated and rainfed wheat are presented, in Table 2. The (CSM)-CERES-Maize model was calibrated by the calculated genetic coefficients of cultivar 'Single Cross 704' by [53]. The calculated coefficients for maize are presented, in Table 3.

For model validation several criteria were calculated to quantify the difference between simulated and observed data. The root mean-squared error (RMSE) is computed to measure the coincidence between measured and simulated values, while mean deviation (RMD) is calculated to evaluate systematic bias of the model. Model efficiency (EF) is calculated to estimate model performance in relation to the observed mean [54]. Moreover, linear regression detected between simulations and observations to evaluate model performance and correlation coefficient (R^2) determined for each simulation.

$$\mathrm{RMSE} = \frac{100}{\bar{O}}\sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}} \tag{1}$$

$$\mathrm{RMD} = \frac{100}{\bar{O}}\sum_{i=1}^{n}\frac{P_i - O_i}{n} \tag{2}$$

$$\mathrm{EF} = 1 - \frac{\sum_{i-1}^{n}(P_i - O_i)^2}{\sum_{i-1}^{n}\left(\bar{O} - O_i\right)^2} \tag{3}$$

where P_i and O_i are simulated and observed data, respectively. $\bar{O}$ is the mean of observed wheat and maize data and n is the number of observations.

2.5. Aridity index

For quantifying drought occurrence in the study locations, Aridity Index [55] was calculated as:

$$\mathrm{AI_U} = P/\mathrm{PET} \tag{4}$$

where P is precipitation (mm) and PET is potential evapotranspiration (mm) (Table 4).

$\mathrm{AI_U}$ was calculated for wheat (irrigated and rainfed) and maize growing seasons (mid-November till June; mid-October till May and mid-May till mid-October, respectively). The potential evapotranspiration was calculated using the [56] equation:

$$\mathrm{ET_o} = 0.0135(\mathrm{KT})R_a(\mathrm{TD})^{0.5}(T + 17.8) \tag{5}$$

$$\mathrm{KT} = 0.00185(\mathrm{TD})^2 - 0.0433(\mathrm{TD}) + 0.4023 \tag{6}$$

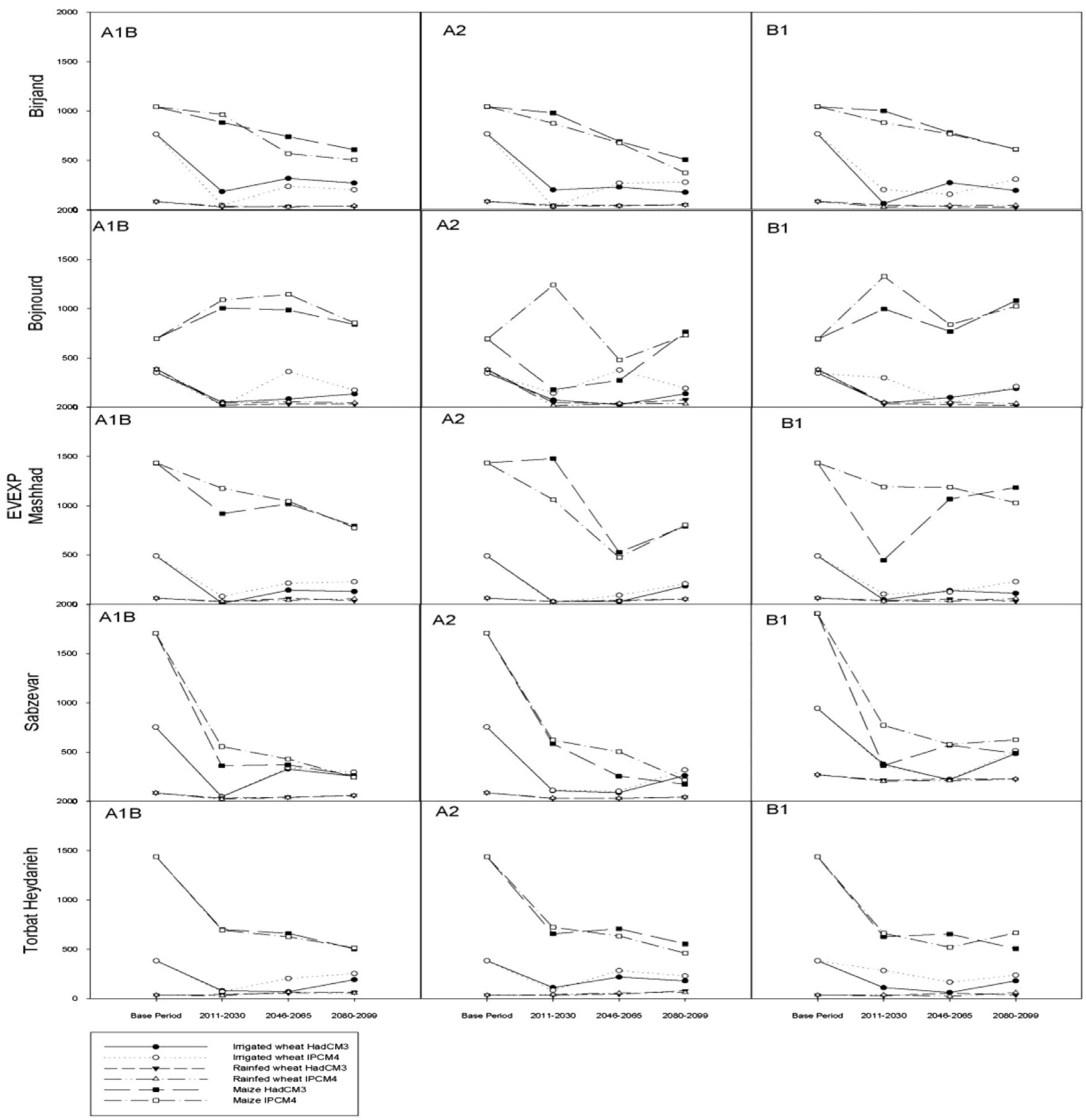

Fig. 7. Estimated values of EV_{EXP} in the growing season in the study locations during the base period and the projected years.

$$TD = T_{max} - T_{min} \tag{7}$$

where ET_o is the potential evapotranspiration (mm), TD is the temperature difference or diurnal temperature range (°C), T_{max} and T_{min} are maximum and minimum temperature (°C), respectively and R_a is extraterrestrial radiation (MJ m^{-2} day^{-1}).

2.6. Vulnerability assessment

In each of the considered dataset, four years were considered for vulnerability assessment. In the base period four dry years were chosen, including 1988, 1995, 2000 and 2003, in the 2011–2030 four years including 2015, 2020, 2025 and 2030, in the 2046–2065 period; 2050, 2055, 2060 and 2065 and in the 2080–2099 years; 2084, 2089, 2094 and 2099 were considered. The quantitative method for assessing vulnerability developed by [7] was adopted by [41] to assess the agricultural vulnerability to different drought conditions in Southern Alberta. This method was also used in this study to quantify the vulnerability of wheat and maize production to drought. In this method vulnerability is considered as a function of three components: sensitivity, well-being state relative to its damage threshold and exposure [41].

$$V_{NEXPi} = SEN \times \frac{W_i}{W_0} \tag{8}$$

where V_{NEXPi} is the vulnerability value without considering the occurrence frequency of the concerned level of drought for a specific year, SEN is the system sensitivity which was calculated as the slope value of the simulated trend line of yield and aridity index during the growing season of each crop. The value of sensitivity can be negative or positive. A negative sensitivity value indicates that the concerned stress is beneficial to the studied system, while a positive value indicates that the stress is harmful to the system [41]. W_i/W_0 is the relative proximity of the crop production well-being to its damage threshold. It is calculated as the proportion of the yield of a specific year to the average yield over the selected years.

$$V_{NEXP} = \bar{V}_{NEXPi} \tag{9}$$

$$V_{EXP} = V_{NEXP} \times EXP \tag{10}$$

where V_{NEXP} is calculated as the average of the V_{NEXPi} of several selected years that are representative of the general drought level to which crop production is exposed. V_{EXP} is the vulnerability value considering the occurrence frequency of the concerned level of drought and EXP is the value of exposure and is calculated as the proportion of years having an AI_U value under the specified level within the concerned period. In this study, three exposure values are calculated respecting the occurrence frequency of two different levels of AI_U, and within two different concerned periods:

1. EXP_L is the occurrence frequency of severe drought from1961 to 2009, from 2011 to 2030, from 2046 to 2065 and from 2080 to 2099. It is calculated as the proportion of years having $AI_U \leq 0.2$ in these years.
2. EXP_S is the occurrence frequency of severe drought from1981 to 2009, from 2021 to 2030, from 2056 to 2065 and from 2090 to 2099. It is calculated as the proportion of years having $AI_U \leq 0.2$ in these years.
3. $EXP_{L'}$ is the occurrence frequency of moderate drought from1961 to 2009, from 2011 to 2030, from 2046 to 2065 and from 2080 to 2099. It is calculated as the proportion of years having $0.2 \leq AI_U \leq 0.5$ in these years.

The possibility of increasing drought frequency considering the exposure trend was calculated as:

$$T_{EXP} = \frac{EXP_S}{EXP_L} \tag{11}$$

where T_{EXP} is the trend of exposure, and represents the increasing or decreasing of severe drought over the base period and simulated years over the recent time. The expected occurrence frequency of severe drought is calculated as:

$$EEXP = EXP_S \times T_{EXP} \tag{12}$$

where EEXP is the expected exposure. The expected vulnerability considering the expected frequency of drought was calculated as:

$$EV_{EXP} = V_{NEXP} \times EEXP \tag{13}$$

The unit of the estimated vulnerability value is the same as that described by [7], which is the unit of well-being factor divided by the unit of the stress measure indicator. Therefore in this study, the unit of vulnerability is the unit of yield (kg/ha) because AI_U does not have unit. The classes of SEN, V_{EXPL}, V_{EXPS}, EEXP and EV_{EXP} have been shown in Table 5 [41].

3. Results

3.1. Crop and climate model evaluation

The evaluation of LARS-WG model indicated a reasonable projection of monthly maximum and minimum temperature (Table 6). All predictions of maximum and minimum temperature showed RMSE values of less than 3.0%. The downscaling model showed high accuracy for precipitation in all stations with RMSE values of less than 7.0%.

The correct estimation of crop yield is very crucial for the successful validation of any given crop growth model at a specific location. Crop model evaluation results showed an adequate accuracy of grain and biomass simulation compared to observed data and a significant correlation was obtained between observed and simulated grain yield and biomass (Table 7, Fig. 2).

Maximum leaf are index for rainfed wheat, Roshan, Falat and Ghods was simulated within ±7.8%, ±7.5%, ±7.7% and ±7.6% of the measured one, respectively. Simulated and observed maximum leaf area index for rainfed wheat, Roshan, Falat and Ghods showed a (R^2=0.92, 0.89, 0.88 and 0.84, respectively) significant correlation (Table 6). The estimated RMSE for maximum leaf area index for maize was ±12.7% and a significant correlation (R^2=0.92) was obtained between observed and simulated values for this parameter. [40] showed that their used crop model predicted maximum leaf are index for Sardari, is ±8% of the measured value (RMSE=8.1), with a significant correlation (R^2=0.94), while [53] showed that the model predicted maximum leaf area index for maize within ±12% of measured values and a significant correlation (R^2=0.94) obtained between observed and simulated values for this parameter.

3.2. Vulnerability assessment

In this study the detrended farm reported historical yields of wheat (irrigated and rainfed) and maize along with simulated yields by DSSAT model for future years were employed as the main data source to measure agricultural well-being in the study area. The expected agricultural vulnerability to possible future drought condition was described based on the expected changes in drought frequency. The estimated agricultural sensitivity to meteorological drought in the growing season based on AI_U during the base period and projected years is presented in Fig. 3. It shows that in all the study locations wheat and maize production were extremely sensitive to drought; the same trend was obtained in the projected years by both HadCM3 and IPCM4 models (SEN > 200). The estimated values of vulnerability without considering the drought occurrence frequency for the selected years in each data set for both crops, in all study locations during base period and projected years were extremely high, V_{NEXPi} > 200 (Appendix Figs. 1–4.). The estimated values of V_{EXPL} and V_{EXPS} are shown in Figs. 4 and 5 respectively.

As described previously (2.6), the vulnerability to drought in this study was measured by considering the value of AI_U below or above a harmful level in a concerned period. V_{EXPL} describes the vulnerability considering the long term frequency of the severely dry condition (Fig. 4), while the effect of a short term frequency of the severe drought (V_{EXPS}) was also calculated (Fig. 5). The results showed that V_{EXPL} and V_{EXPS} during the base period and the simulated years in all the study locations and under all scenarios were extremely high for both crops (V_{EXPL}, V_{EXPS} > 20).

The estimated values of EEXP in the study locations during the base period and the simulated years are shown in Fig. 6. The expected exposure in all the study locations were low (EEXP < 1). EEXP may not reflect the real situation of drought occurrence in the future, it sheds some light on climate conditions in the study area. The estimated value of expected vulnerability with exposure (EV_{EXP}) is presented in the Fig. 7. The estimated values in all study locations were extremely high (EV_{EXP} > 2.5). The only exceptions were under A2 scenario for 2011–2030 using HadCM3 in Bojnourd for irrigated wheat with a moderate value and using IPCM4 for maize in Mashhad EV_{EXP} were high. It is expected that wheat and maize production in the study locations to be affected by drought in the simulated years, the same as the base period.

4. Discussion

The results showed that wheat and maize production the base period have suffered from severe drought. It was reported that

Iran has experienced 17 droughts till now; the most severe one occurred during 1999–2000 [57] and the negative effects of drought during 2000–2006 reduced the cultivated area of wheat. The negative effects of drought can be related to its effects on the growing season length of crops which is effective on dry matter accumulation, respiration rate and their productivity [58]. Moreover drought can decrease seed filling period, accelerates the anthesis and maturity of winter crops and affects the pollination [59]. Drought was also recognized as one of the key causes of interannual yield variability of wheat and barley during 1985–2005 in some areas of Khorasan [39]. A decline in barley yield affected by drought during base period in Semnan province in Iran was also reported [60].

The results of both GCM models showed the same trend under all scenarios for both irrigated and rainfed wheat and maize production. As the estimated values of SEN, V_{EXPL}, V_{EXPS} and EV_{EXP} in the coming future years were extremely high, while EEXP was low. It seems that in the study locations drought is going to affect wheat and maize production in the future years. These negative effects can be related to higher temperatures that accelerate the grains growth and reduces the length of time that seeds have to grow and mature which can reduce final yields [61]. It is reported that globally, the drought disaster-affected area will increase with rising global temperature, from 15% to 44% by 2100. Correspondingly, the rates of yield reduction related to drought disaster for major crops will increase significantly under future climate change by $>50\%$ in 2050 and almost 90% in 2100 [62]. It is reported that the factors that made rice and wheat crops vulnerable to drought were quite consistent, while those of maize crops varied considerably depending on the type of region. This is likely due to the fact that maize is produced under very different conditions worldwide [63]. It is predicted that the future production of rainfed wheat in Khorasan province under climate change to decline during the next 80 years [64]. It is projected that the maize productivity under climate changes in Northeast of Iran to decrease from -1% to -39% during future 100 years [53]. This reduction was related to the reductions in crop growing season (time from sowing to harvest) which is due to positive and direct relation between the rate of development and temperature [31]. The reduction in the wheat growing season length under all scenarios of climate change was also reported in Sistan and Baluchestan region in Iran, which affected wheat production negatively [65]. Evaluation of rice and wheat vulnerability in Northwest of India to future changes in climate showed that acute water shortage conditions combined with the thermal stress should adversely affect both wheat and more severely, rice productivity in this region even under the positive effects of elevated CO_2 in the future [66].

5. Conclusions

The approach based on the collected yield data during the base period is employed to analyze agricultural vulnerability to drought. The results showed that wheat (irrigated and rainfed) and maize production is vulnerable to severe droughts during the base period in the study areas. Based on simulated crop yields, the agricultural vulnerability in the projected years are similar to the base period; extremely sensitive and vulnerable to drought. The results show the significance of mitigation as a key component of reducing climate change and drought negative impacts on wheat and maize production under different climate change scenarios in Khorasan Province of Iran. Overall, the adopted and modified method for quantitative vulnerability assessment is demonstrated to be effective in assessing the magnitude of agricultural vulnerability to varying drought conditions in Northeast of Iran. Similar applied data will be required for extension of this approach to other geographical locations.

Appendix A

See Fig A1, Fig A2, Fig A3 and Fig A4.

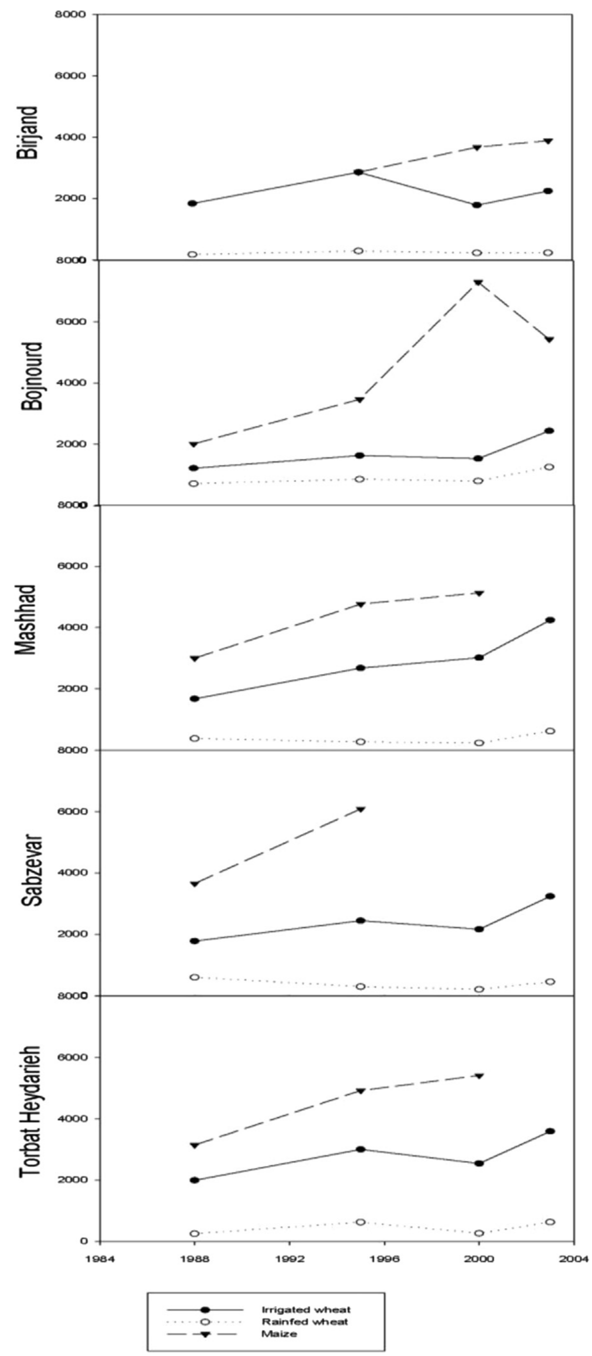

Fig. A1. The estimated values of V_{NEXPi} in the study locations in the selected years (1988, 1995, 2000 and 2003) during the base period.

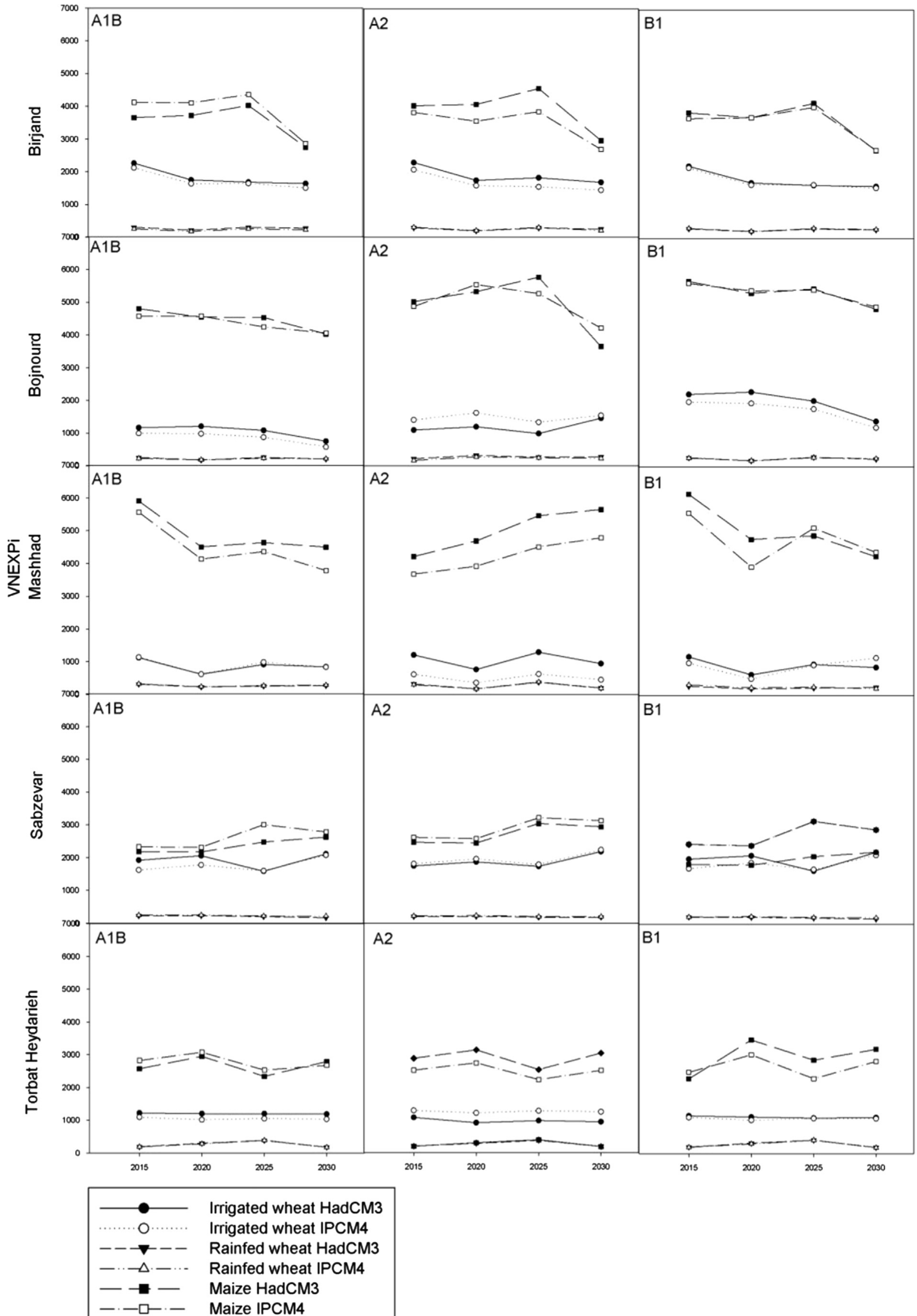

Fig. A2. The estimated values of $V_{\mathrm{NEXP}i}$ in the study locations in the selected years (2015, 2020, 2025 and 2030) during the simulated years of 2011–2030.

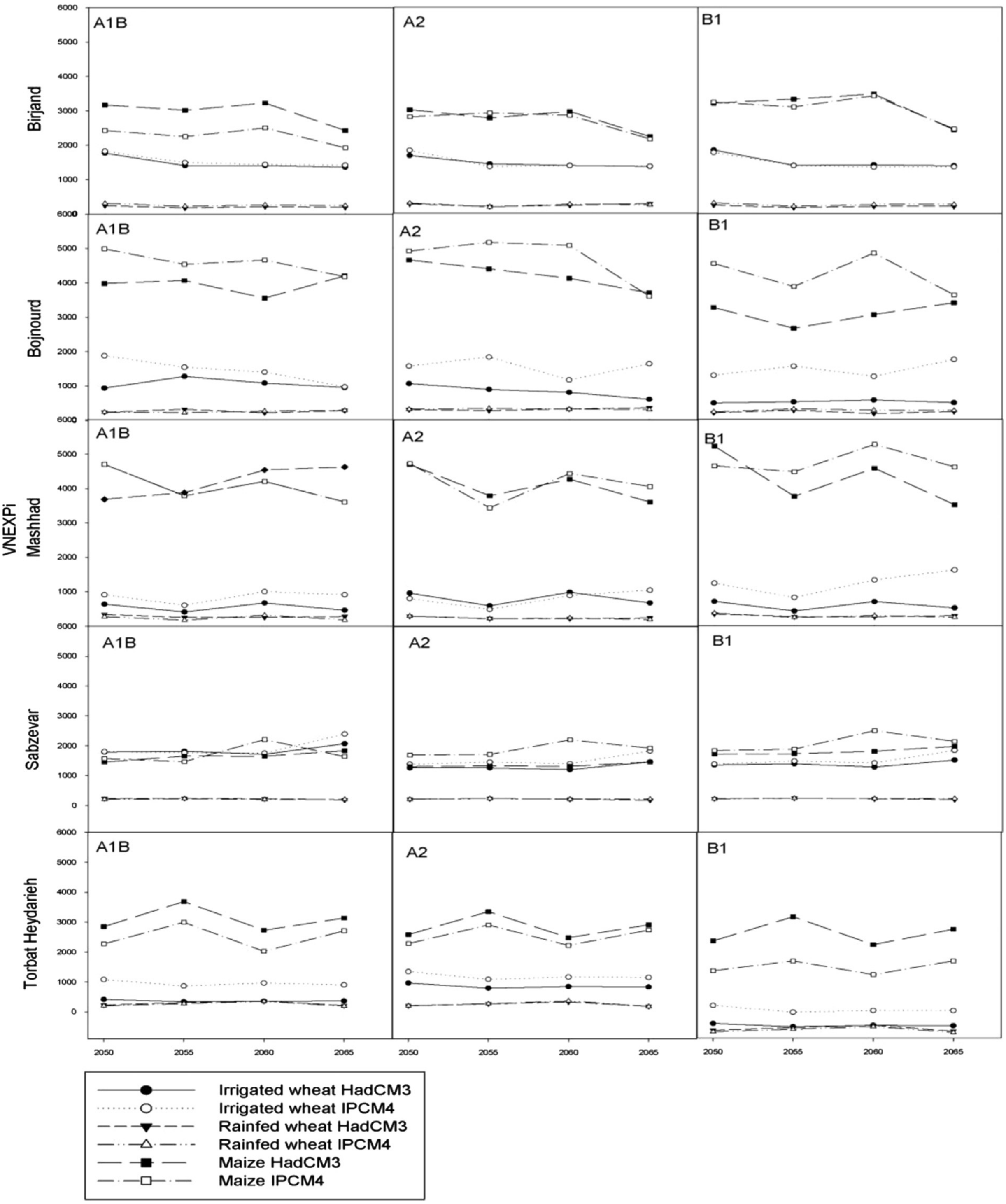

Fig. A3. The estimated values of $V_{\mathrm{NEXP}i}$ in the study locations in the selected years (2050, 2055, 2060 and 2065) during the simulated years of 2046–2065.

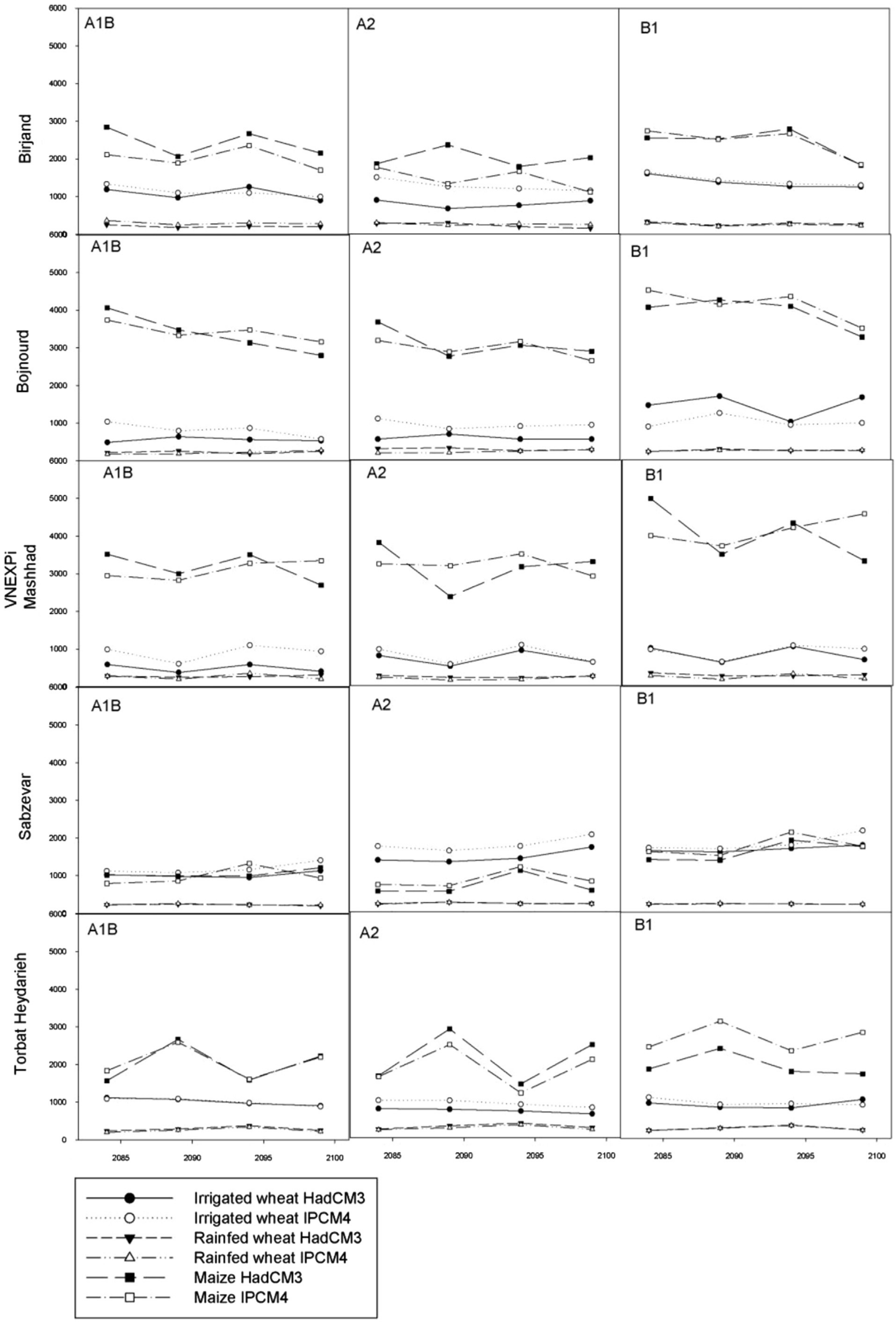

Fig. A4. The estimated values of V_{NEXPi} in the study locations in the selected years (2084, 2089, 2094 and 2099) during the simulated years of 2080–2099.

Appendix B. Supporting information

Supplementary data associated with this article can be found in the online version at. These data include Google maps of the most important areas described in this article.

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