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ORIGINAL PAPER

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Abstract Wheat is the main food for the majority of Iran's population. Precise estimation of wheat yield change in future is essential for any possible revision of management strategies. The main objective of this study was to evaluate the effects of climate change, CO_2 concentration, technology development and their integrated effects on wheat production under future climate change. This study was performed under two scenarios of the IPCC Special Report on Emission Scenarios (SRES): regional economic (A2) and global environmental (B1). Crop production was projected for three future time periods (2020, 2050 and 2080) in comparison with a baseline year (2005) for Khorasan province located in the northeast of Iran. Four study locations in the study area included Mashhad, Birjand, Bojnourd and Sabzevar. The effect of technology development was calculated by fitting a regression equation between the observed wheat yields against historical years considering yield potential increase and yield gap reduction as technology development. Yield relative increase per unit change of CO_2 concentration (1 ppm^{-1}) was considered 0.05 % and was used to implement the effect of elevated CO_2. The HadCM3 general circulation model along with the CSM-CERES-Wheat crop model were used to project climate change effects on wheat crop yield. Our results illustrate that, among all the factors considered, technology development provided the highest impact on wheat yield change. Highest wheat yield increase across all locations and time periods was obtained under the A2 scenario. Among study locations, Mashhad showed the highest change in wheat yield. Yield change compared to baseline ranged from −28 % to 56 % when the integration of all factors was considered across all locations. It seems that achieving higher yield of wheat in future may be expected in northeast Iran assuming stable improvements in production technology.

Keywords Climate change scenario · General circulation models · Simulation · Technology improvement

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Introduction

Agricultural production is highly vulnerable to climate change. The effect of climate change on crop production has been studied using Global Circulation Models (GCM) together with crop growth simulation models under various scenarios in different parts of the world (Challinor et al. 2005; Hussain and Mudasser 2007). The IPCC has defined standard greenhouse gas emission scenarios to project climate change based on various socioeconomic, technological and energy use factors (IPCC 2007). The SRES-A2 scenario considers a very heterogeneous world condition with high population growth rate, slight economic development and slow technological change (Prudhomme et al. 2010). The SRES-B1 scenario defines a convergent world with a global population that peaks in mid-century, with rapid changes in economic structures towards a service and information economy (Wetterhall et al. 2009).

Due to high reliance on energy production from fossil fuels, the CO_2 concentration in the atmosphere has increased from about 275–280 ppm to 370 ppm since 1750 (Etheridge et al. 1996; Keeling and Whorf 2000) and may reach 600–1,000 ppm by the end of this century (Cox et al. 2000). The positive effect of increasing CO_2 concentration on photosynthetic rates and photorespiration, especially for C_3 crops, is well documented. Various studies showed that the yield of many crops in response to elevated CO_2 will increase if the other factors are considered unchanged (Amthor 2001; de Costa et al. 2006; Bannayan et al. 2005; Yoon et al. 2009). Crop yield in dryland regions is determined mainly by precipitation and is extremely vulnerable to changes in precipitation patterns and amounts. Furthermore, this vulnerability increases with the decrease in total precipitation. Based on the climate change projections of GCMS, future changes of global average temperature are expected to be between 2 °C and 4.5 °C in this century (IPCC 2001) and some regional areas would be even warmer than the global average (Giorgi and Bi 2005). Increasing temperature affects physiological processes such as photosynthesis, respiration and partitioning of photosynthesis production (Chartzoulakis and Psarras 2005; Yang and Zhang 2006).

Analysis of 50-year trends of wheat production in Iran has shown that the increased area of wheat cultivation, especially during the past 10 years, did not significantly increase yields, and higher production was due mainly to higher yield per unit area due to technology development (Koocheki et al. 2003). Technology development such as new cultivars, fertilizer, pesticides, machinery, irrigation, and other factors have been largely responsible for yield increase in past decades (Evans 1997; Amthor 1998; Reynolds et al. 1999). Thus, to accurately calculate the yield change in future it is necessary to consider technology development in addition to climate variables change and CO_2 effects (Ewert et al. 2005).

Current estimates indicate that Iran may need over 20 million tons wheat grain by 2020 (Zarea et al. 2006). Studies on climate change at a global scale have reported a reduction of rainfed and irrigated wheat yield by 10–40 % and 20–50 %, respectively (Parry et al. 1999, 2004). Studies conducted at a national scale by Eyshi Rezaie and Bannayan (2012) using the HadCM3 General Circulation Model under the A_2 scenario and using a DSSAT crop simulation model projected that rainfed wheat yield in Kashafrood basin will reduce by 50 % in the 2040–2069 period.

The main aim of the present study was to estimate wheat yield change in the Khorasan province of Iran under future climate change conditions, by evaluating the combined effects of change of temperature, CO_2 concentration, precipitation and technology development.

Methods

Study area

Khorasan province covers an area of about 248,000 square kilometers in northeast Iran. This extensive area is inhabited by more than 6 million people and agriculture plays the main economic role. Khorasan experiences a highly fluctuating climate (Bannayan et al. 2010); however, rainfed farming is the most common cultivation pattern in this area due to the semi-arid conditions. Mashhad, Birjand, Bojnourd and Sabzevar—all located between 32° and 37° N latitude —are the dominant agricultural regions in Khorasan. The climatic characteristics of the study region are presented in Table 1. Average precipitation across Khorasan province during the last 40 years was 222 mm and varies from about 169 mm at the southern area (Birjand) to 269 mm in northern areas (Bojnourd). Generally, rainfall is rare from July to September (IMO 2009).

Effects of climate change

Data set

The GCM model (United Kingdom Met Office Hadley Center: HadCM3) (Mitchell et al. 1995) under two scenarios

Table 1 Climatic features of the study locations. Length of the growing season (GS) = 200 days. *LAT* Latitude, *LONG* longitude, *Tmax* mean of maximum temperature in GS, *Tmin* mean of minimum temperature in GS; *Sunshine hours*

Location	LAT	LONG	Altitude (m)	Annual precipitation (mm)	Tmax (°C)	Tmin (°C)	Seasonal mean temperature (°C)	Sunshine hours[a]
Mashhad	36.16	59.38	999	256.4	31.1	15	23.4	329.8
Sabzevar	36.12	57.43	977.6	192.1	34.5	19.7	27.7	323.7
Bojnourd	37.28	57.19	1,091	269.2	29.2	14.5	22.2	300.1
Birjand	32.52	59.12	1,491	169.6	33.3	16	25.6	333.3

[a] Sunshine hours in the GS

(SRES-A2 and SRES-B1) was used to project climate change in this study. HadCM3 is coupled to atmosphere-ocean GCMs as described by Gordon et al. (2000). Daily climate data, including maximum and minimum temperature (°C) and precipitation (mm) were obtained for the period 1980–2005 from Mashhad, Birjand, Bojnourd and Sabzevar climatological stations.

In this study, LARS-WG was used to produce daily data of climate variables as one stochastic growing season for each projection period. This 1-year data included maximum and minimum temperature and precipitation of each location for four projection time [1980–2005 (baseline), 2020, 2050 and 2080]. LARS-WG is a stochastic weather generator based on the series approach (Semenov and Stratonovitch 2010) that produces a synthetic daily time series of maximum and minimum temperature, precipitation and solar radiation. LARS-WG applies observed daily weather data for a given site to compute a set of parameters for probability distributions of weather variables as well as correlations between them (Semenov and Brooks 1999).

Crop model calibration

The Decision Support System for Agrotechnology Transfer (DSSAT) is comprised of six models for simulating the growth of 16 crops of economic importance (Jones et al. 2003). The model has demonstrated high reliability under different climates, soil, and management conditions (Bannayan et al. 2003). DSSAT showed the best performance on estimation of winter wheat production across eight crop growth simulation models (Palosuo et al. 2011). The CSM-CERES Wheat model is one of the most popular and highly reliable wheat models (Rinaldi 2004) and has been evaluated in many sites across the world; results indicate its capacity to simulate grain yields under different climatic conditions (Pecetti and Hollington 1997). The crop model was calibrated based on an experiment conducted in the year 2000 at experimental station of the College of Agriculture, Ferdowsi University of Mashhad (latitude: 36°15′ N, longitude: 59° 28′ E: 928 m) in the central part of Khorasan province. In this experiment, the effects of planting density and different cultivars of wheat were investigated under Khorasan province conditions. Three planting density levels (250, 300 and 350 plants m^{-2}) and two wheat cultivars (Sardari and Sabalan) were evaluated in a factorial experiment based on a randomized complete block design with three replications (Sharifi and Rahimian Mashhadi 2001). Observed grain yield, biological yield, leaf area index (LAI) at different growth stages, plant height, tiller numbers, 1,000 seed weight, days to heading and days to maturity, harvest index and spikelet number per square meter of ground were provided as the required input of the crop model. The genetic coefficients of Sardari cultivar, which are required as model input, are presented in Table 2.

Table 2 Genetic coefficients of Sardari cultivar. *P1V* Days at optimum vernalizing temperature required to complete vernalization, *P1D* percentage reduction in development rate in a photoperiod 10 h shorter than the threshold relative to that at the threshold, *P5* grain filling (excluding lag) phase duration (°C days), *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 days)

P1V	P1D	P5	G1	G2	G3	PHINT
1	40	450	13	41	1.5	60

Field experiments

Two-years of field experiment data from two diverse locations were used for crop model validation. Of the two experiments used for validation, the first was conducted in the year 2000 in Shirvan Dryland Agricultural Research Institute located 50 km from Mashhad. This experiment investigated the impacts of different planting densities on yield and yield components of wheat (Sharifi and Rahimian Mashhadi 2001). Five levels of planting densities (200, 250, 300, 350 and 400 plants m^{-2}) and two levels of irrigation (rainfed and supplement irrigation) under a split plot factorial experiment based on a randomized complete block design with three replications was considered in the experiment. The second experiment (1998) aimed to investigate the impact of different levels of phosphorus and seed rate on yield of wheat (Koocheki and Azemzade 1999). In both experiments, Sardari wheat cultivar was cultivated. Time series of dry weight and maximum LAI were measured in both experiments. The simulation model options were set according to weather, soil and treatments employed in these two experiments.

Crop model validation

Several criteria were calculated to quantify the difference between simulated and observed data. The relative root mean-squared error (rRMSE), which measures the coincidence between measured and simulated values, was calculated to evaluate systematic bias of the model. Model efficiency (EF) was calculated to estimate model performance in relation to the mean of the observed data (Nash and Sutcliffe 1970). Moreover, linear regression was applied between simulations and observations to evaluate model performance and correlation coefficient (R^2) for each simulation.

$$rRMSE(\%) = \left[\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}\right]^{0.5} \times \frac{100}{\overline{O}} \quad (1)$$

$$EF = 1 - \frac{\sum_{i=1}^{n}(p_i - o_i)^2}{\sum_{i=1}^{n}(\overline{o} - o_i)^2} \quad (2)$$

Where P and O are simulated and observed data, respectively, in addition $\overline{O}$ is the mean of observed data and n is the number of observations. The rRMSE illustrates the model's prediction error. The EF indicates the efficiency of the model and can have positive or negative values (Huang et al. 2009; Bannayan and Hoogenboom 2008).

Climate model uncertainty

Climate model uncertainty analysis was performed by two methods. First of all, uncertainty of maximum and minimum temperatures and precipitation was evaluated by comparison between mean observed and simulated values considering the normal distributions of these variables in all study locations (Khan et al. 2006). In addition, uncertainty was evaluated by the Wilcoxon rank sum method as a non-parametric test. This test is an alternative to the two-sample *t*-test that is based solely on the order in which the observations from the two samples fall (Conover 1980). Based on the Wilcoxon rank sum method, if the *P*-value is more than 0.05, there is no significant differences between populations and vice versa.

Effects of technology development

Technology development is the main factor to have caused increasing crop yields, especially wheat, during recent decades in the study region. Therefore it is necessary to consider the effects of technology development if we are to estimate yield change in the future. In this study, we considered all measures related to crop management that result in higher yield, including pesticides, fertilizers, irrigation and machinery, as technology development. Technology development was divided into two main components: one raising yield potential ($f_{T,P}$) and the other lessening the gap between actual and potential yields ($f_{T,G}$) (Ewert et al. 2005). In order to evaluate the effects of technology development on yield changes in the future, historical yield trends of wheat were calculated based on data provided by the Ministry of Agriculture of Khorasan province. Yield trends were calculated by fitting a linear regression through the observed data for each location in the 25-year period from 1981 to 2005.

$$Y_e = a + r_y.t \quad (3)$$

Where Y_e is the estimated yield at a particular year t, r_y is the annual rate of yield change and a is interception point. The regression equation that fitted between observed yields and different years for each location is presented in Table 3. Relative yield change (Y_r) between years was calculated according to Ewert et al. (2005) as:

$$Y_r = \frac{Y_e(t)}{Y_e(t-1)} \quad (4)$$

Where Y_r was calculated from the fitted regression line of observed yields (25 years) mentioned in Eq. 3. The baseline in our study was 2004–2005. Thus, the future change in yield as affected by technology development compared to baseline year (P_{t0}) was calculated from relative yield change at baseline and a factor to consider the effects of technology on potential yield and yield gap (Ewert et al. 2005):

$$\frac{P_{t,T}}{P_{t_0}} = Y_r(t_0) + \int_{t_0}^{t=t_s}\left(\frac{Y_{r,a}.f_{T,P(t)}.f_{T,G(t)}}{0.5}\right)dt \quad (5)$$

$P_{t,T}$ is the future yield of wheat as affected by technology development, $Y_r(t_0)$ is the relative yield change in the baseline year, $Y_{r,a}$ is the annual increase of relative yield change with reference to the baseline and is calculated from: $[Y_r(t_0)-1]$. For example, if relative yield change for the baseline year is 1.044 in Mashhad (Table 3), and the annual increase of yield for 25 years was 0.044, future yield might be 1.41 times the yield at baseline. According to Nassiri and Koocheki (2010a), the present yield of wheat is about 50 % of potential yield in Iran so a value of 0.5, indicating the relative share of current yield of potential yield, was used in this study. This value in European countries is about 0.8 (Oerke and Dehne 1997). The values of $f_{T,P}$ and $f_{T,G}$ for

Table 3 Fitted regression equations between observed yields and years in different locations. Y_r Relative yield change, R^2 coefficient of determination

Location	Regression equation	R^2	Y_r (2005/2004)
Mashhad	Y_e=−170.4+0.086 t	0.61*	1.044
Sabzavar	Y_e=−136.1+0.069 t	0.53*	1.030
Birjand	Y_e=−82.2+0.042 t	0.47*	1.022
Bojnuord	Y_e=−142.5+0.073 t	0.44*	1.019

*Significant at 5 % level of probability, ** significant at 1 % level of probability, ns non-significant

Table 4 Values of $f_{T,P}$ and $f_{T,G}$ for calculating of technology development effects and projected increasing of CO_2 concentration (ppm) on change of wheat yield for different scenarios of the IPCC and time periods

Parameter	Year	Scenario	
		A2	B1
$f_{T,P}$	2020	0.5	0.4
	2050	0.3	0.2
	2080	0.1	0.0
$f_{T,G}$	2020	0.55	0.55
	2050	0.60	0.60
	2080	0.65	0.65
CO_2	2020	424	417
	2050	537	484
	2080	709	518

different scenarios were determined based on Ewert et al. (2005, Table 4). The Sardari cultivar, which has been cultivated for about 20 years in the Khorasan region, is a variety of rainfed wheat used commonly in Iran (Khorasan Ministry of Agricultural Statistics 2008).

Effects of CO_2 concentration

The calculation of CO_2 effect on yield was based on estimation of future CO_2 concentration by IMAGE model (IMAGE-team 2001; Table 4). According to the results of Koocheki and Nassiri (2008), average yield change of wheat per unit increase of CO_2 concentration is 0.05 $\%\text{ppm}^{-1}$ suggesting that increase in CO_2 concentration from current (350 ppm) to, e.g., 550 and 700 ppm would increase wheat yield by 10 % and 17.5 %, respectively. In order to calculate the CO_2 effect on change of wheat yield, the relative yield change in future conditions compared with the baseline as affected by CO_2 concentration was calculated according to Ewert et al. (2005) as:

$$\frac{P_{t,co}}{P_{t_0}} = \frac{f_{co,r}.\Delta C_{t-t_0}}{100} + 1 \qquad (6)$$

Where $P_{t,co}$ is the future yield of wheat as affected by increasing CO_2 concentration, $f$co,r is the relative yield change per unit increase of CO_2 concentration (0.05 %) and ΔC_{t-t0} is the difference between future and current CO_2 concentration.

Factors integrative effects

Accurate estimation of yield change in future needs to integrate the effects of all factors (climate change, CO_2 and technology development). For this purpose, according to Ewert et al. (2005), the integrated effects were calculated as:

$$\frac{p_{t_0}}{p_t} = \frac{1}{1 + \left(\left(\frac{p_{t,cl}}{p_{t_0} - 1}\right) + \left(\frac{p_{t,co}}{p_{t_0} - 1}\right) + \left(\frac{p_{t,T}}{p_{t_0} - 1}\right)\right)} \qquad (7)$$

Where P_t is the future yield as affected by all factors and $P_{t,Cl}$ is relative yield change as affected by climate change in comparison with baseline year.

Table 5 Observed and simulated values of grain yield, crop biomass and maximum leaf area index (LAI)

	Grain yield (kg ha^{-1})	Crop biomass (kg ha^{-1})	Maximum LAI
Observed	3,300	10,920	2.925
	3,507	11,050	3.42
	3,543	11,154	3.42
	3,567	11,237.2	3.15
	3,510	11,174.8	3.96
Simulated	3,000	10,400	2.7
	3,552	10,790	3.15
	3,441	10,374	3.15
	3,417	10,920	3.15
	3,327	10,660	3.6

Results

Crop and climate model evaluation

The values of observed and simulated grain yield, crop biomass and maximum LAI are listed in Table 5. Crop model evaluation results showed an adequate accuracy of grain (rRMSE=5.31 %) and biomass (rRMSE=4.81 %) simulation (Table 6) and a significant correlation was obtained between observed and simulated grain yield and biomass (R^2=0.88 for grain yield and R^2=0.51 for biomass production) (Table 6). Crop model, simulated maximum LAI within ±8 % of the observed data (rRMSE=8.1 %), and there was a significant correlation (0.94) between observed and simulated values of maximum LAI (Table 6).

Table 6 Comparison of simulated and observed grain and biological yield and maximum LAI by relative root mean-squared error (rRMSE), Model efficiency (EF) and R^2 values

Parameter	rRMSE (%)	EF	R^2
Grain yield	5.31	0.10	0.88
Crop biomass	4.81	−4.7	0.51
Maximum LAI	8.10	0.19	0.94

The absolute errors of the downscaling model [absolute differences between observed mean of daily climatic data (1940–2005) and climate projections] in approximation of the mean daily precipitation, daily maximum and minimum temperatures for each month are shown in Fig. 1. Deviations (referred to as simulation errors) between downscaled and observed monthly means were tested by non-parametric Wilcoxon rank-sum test at 95 % confidence level. The results showed that the simulation error was significantly higher for precipitation than for maximum and minimum temperatures (Fig. 1). Simulation errors of precipitation were different across all study locations. Mashhad and Bojnourd exhibited the highest error during winter months (January–March) and summer months for drier locations (Birjand and Sabzevar) (Fig. 1). Wilcoxon rank-sum test showed insignificant differences for all months at 5 % significance level, except for September and October in Sabzevar and Birjand for minimum and maximum temperatures, respectively (Table 7). In addition, Bojnourd (September), Birjand (March) and Sabzevar (April) indicated significant error in the precipitation simulation (Table 7).

Effect of climate variables change

Wheat yield decreased due to climate change (based on changing precipitation and temperature) in comparison with the baseline year 2005. Climate change led to a reduction in wheat yield of 3 % to 50 % for different locations and years (Table 8). However, in some cases wheat yield increased, ranging from 7 % (Mashhad location under B1 scenario in 2080) to 13 % (Birjand location under B1 scenario in 2080) compared to the baseline year (Table 8). Under the B1 scenario, climate change had no effect on wheat yield for Mashhad and Birjand locations in 2020 and 2050 (Table 8). The highest yield reduction (50 %) was obtained for Mashhad and Bojnuord under scenario A2 and the highest yield increase (13 %) was obtained for Birjand.

Effect of technology development

Wheat yield change as affected by technology development differed among various locations, scenarios and years (Table 8). The effect of technology development on wheat yield was in the range of 3 % (Birjand and Bojnuord, B1, 2080) to 75 % (Mashhad, A2, 2050) compared to the baseline year of 2005 (Table 8). Yield change under scenario A2 was higher than B1 because of higher values of $f_{T,P}$ and $f_{T,G}$ under scenario A2 (Table 4). Mashhad and Bojnuord showed maximum and minimum changes of yield due to technology development in all years, respectively (Table 8).

Effect of CO_2

The effect of higher CO_2 concentration on yield differed among years and scenarios but not among locations. This might be due to the fact that change of CO_2 concentration is global and not regional. The change of yield due to CO_2 ranged from 3 % to 18 % depending on year and scenario compared to baseline year (Table 8). The highest yield change by CO_2 was under scenario A2 in 2080 and lowest under scenario B1 in 2020 (Table 8). Yield change showed a higher increasing slope under scenario A2 than under B1 due to the lower increase in CO_2 concentration under scenario B1 (Table 4). Elevated CO_2 concentration stimulates the rate of photosynthesis and causes higher biomass and economic yield of crops (de Costa et al. 2006; Bannayan et al. 2009).

Factors integrative effects

The effect of all factors together including climate change, CO_2 and technology development on change of wheat yield is very important. The results showed that wheat yield change compared to baseline was highest for Mashhad and this change ranged from 19 % to 53 % (Table 8). The projection for the Bojnuord location showed lower change of yield than other locations. Estimated yield change as affected by integrated effects of all factors showed negative and positive impacts and yield ranged from −28 % to 56 % for all locations (Table 8). The simulated yields as affected by all factors showed that the highest yield was achieved for Sabzevar and Bojnourd underscenario A2 and the lowest values of yield was obtained for Birjand under A2 (Fig. 2).

Discussion

Our results illustrate that technology development, CO_2 concentration and climate change all play a vital role in determination of future agricultural production. However, focus on combination of these factors, especially technology development, has not yet been adequately considered. Technology development had a higher impact on agriculture production than climate change and higher CO_2 concentration. Crop physiologists indicate that there is still room for yield improvements of crops by increasing potential yields and reducing the yield gap (Evans 1997; Austin 1999; Reynolds et al. 1999).

Increasing potential yields may be achievable through improved light capture and light and nitrogen use efficiency (Loomis and Amthor 1999; Borlaug 2000). Improved pest management and biotechnology achievements via the use of plants resistant against pests and disease and plants tolerant

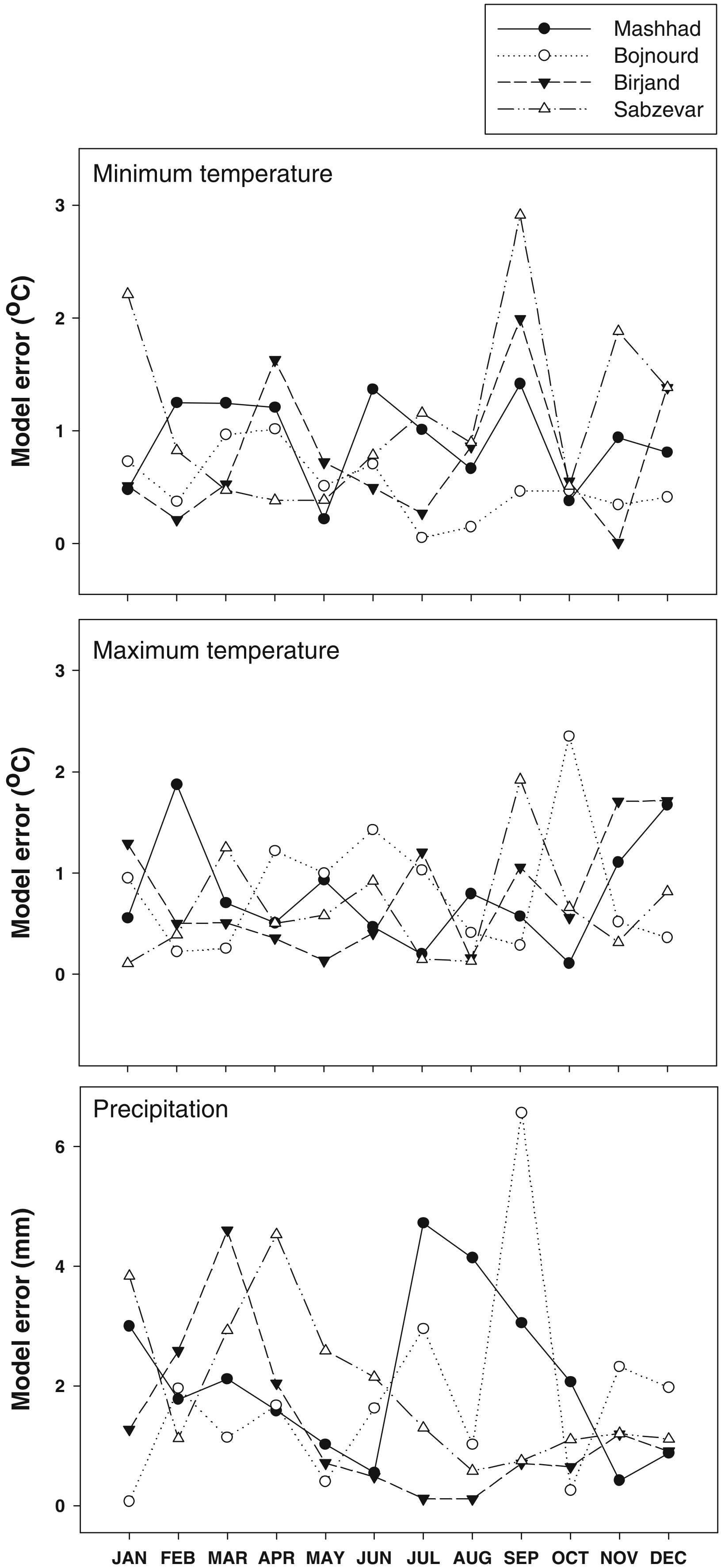

Fig. 1 Model errors (absolute values) in downscaled daily maximum and minimum temperature and precipitation

Table 7 Test results (*P*-values) of the Wilcoxon rank sum test for the difference of means of observed and downscaled daily maximum and minimum temperature and precipitation at 95 % confidence level. *Tmin* Minimum temperature, *Tmax* maximum temperature, *Pre* precipitation

Month	Mashhad			Bojnourd			Birjand			Sabzevar		
	Tmin	Tmax	Pre	Tmin	Tmax	Pre	Tmin	Tmax	Pre	Tmin	Tmax	Pre
January	0.532	0.473	0.221	0.542	0.482	0.531	0.352	0.313	0.345	0.058	0.204	0.115
February	0.171	0.152	0.167	0.344	0.375	0.266	0.245	0.218	0.155	0.254	0.226	0.249
March	0.215	0.191	0.287	0.267	0.291	0.437	0.369	0.328	0.047	0.157	0.140	0.210
April	0.144	0.158	0.238	0.183	0.199	0.299	0.163	0.145	0.218	0.148	0.132	0.036
May	0.342	0.376	0.342	0.589	0.524	0.477	0.456	0.406	0.369	0.351	0.312	0.284
June	0.098	0.108	0.198	0.254	0.226	0.206	0.562	0.500	0.550	0.542	0.482	0.531
July	0.157	0.173	0.157	0.441	0.481	0.529	0.371	0.330	0.363	0.153	0.136	0.150
August	0.357	0.318	0.350	0.365	0.325	0.357	0.261	0.232	0.256	0.473	0.421	0.463
September	0.294	0.262	0.523	0.148	0.132	0.012	0.114	0.101	0.112	0.042	0.061	0.067
October	0.421	0.459	0.305	0.387	0.023	0.161	0.423	0.402	0.603	0.254	0.277	0.305
November	0.573	0.510	0.161	0.251	0.223	0.246	0.242	0.230	0.253	0.157	0.140	0.154
December	0.722	0.143	0.572	0.392	0.349	0.244	0.089	0.214	0.363	0.243	0.216	0.238

to biotic and abiotic stresses may result in a reduction of the gap between actual and potential yield (Borlaug 2000; Miflin 2000). This is considered as a continuing positive effect of technology development on production change for

Table 8 Effects of climate change, technology development, CO_2 and all factors together on yield change of wheat under different scenarios of IPCC and time periods compared to the baseline (2005) in different locations of Khorasan province

Factor	Scenario	Year	Location			
			Mashhad	Sabzavar	Birjand	Bojnuord
Climate change	A2	2020	0.9	0.8	0.81	0.5
		2050	0.5	0.87	1.09	0.8
		2080	0.88	0.93	1.09	0.63
	B1	2020	1	0.78	0.79	0.87
		2050	0.8	0.82	1	0.95
		2080	1.07	0.88	1.13	0.97
Technology development	A2	2020	1.41	1.30	1.20	1.18
		2050	1.76	1.55	1.38	1.33
		2080	1.47	1.34	1.24	1.20
	B1	2020	1.33	1.24	1.17	1.14
		2050	1.52	1.38	1.26	1.22
		2080	1.04	1.03	1.02	1.02
CO_2	A2	2020	1.04	1.04	1.04	1.04
		2050	1.09	1.09	1.09	1.09
		2080	1.18	1.18	1.18	1.18
	B1	2020	1.03	1.03	1.03	1.03
		2050	1.07	1.07	1.07	1.07
		2080	1.08	1.08	1.08	1.08
All factors	A2	2020	1.35	1.14	1.05	0.72
		2050	1.35	1.51	1.56	1.22
		2080	1.53	1.45	1.51	1.01
	B1	2020	1.36	1.05	0.99	1.04
		2050	1.39	1.27	1.33	1.24
		2080	1.19	0.99	1.23	1.07

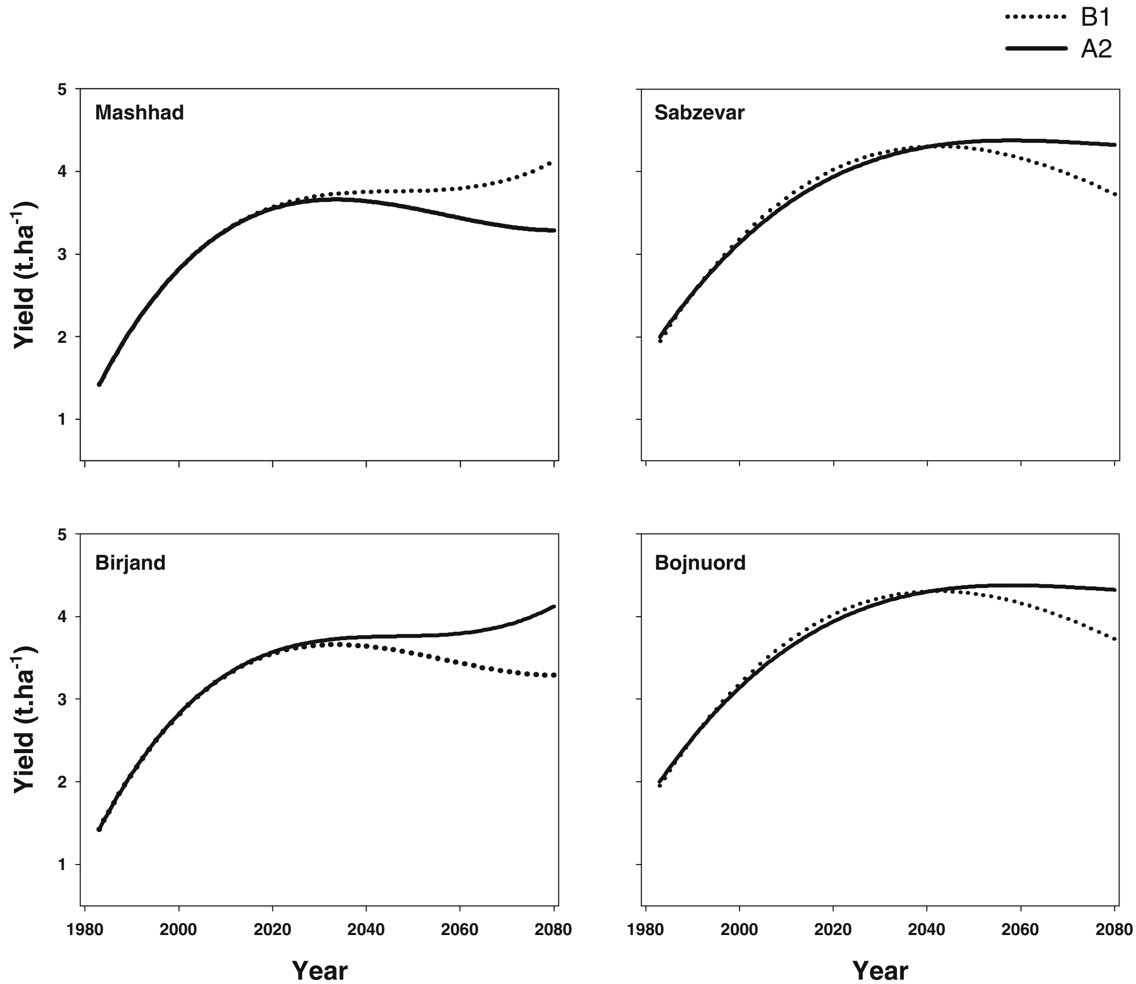

Fig. 2 Historical trend and integrative effects of future climate change, technology development, and CO_2 on wheat yield in Mashhad, Sabzevar, Birjand and Bojnourd under different scenarios of IPCC (A2 and B1)

the future. Ewert et al. (2005) estimated the effect of technology development on wheat yield under different scenarios in the future and reported an increasing crop productivity ranging between 20 % and 134 %.

Yield gap analysis indicated that actual yield reached 50 % of potential yield, indicating that the yield gap of wheat has been bridged due to improved management practices (Nassiri and Koocheki 2010a). Therefore, improvement of management strategies showed a greater influence on winter wheat yield increase compared to the release of new cultivars when considering cultivation of old rainfed wheat cultivars such as Sardari during the last 25 years in the northeast of Iran (Nassiri and Koocheki 2010b).

Rainfed agricultural systems started to transform traditional practices to a semi-industrial management style from the 1990s onwards in the semi-arid region of northeast Iran, and are the main reason for the increasing yield trend during last 25 years in this region. The slope of yield enhancement was higher in Mashhad compared to the other study locations. Mashhad is the capital city of the Khorasan province and, due to agricultural facility centralization and introduction of new management practices in the center of the province, yield increase trend is higher in Mashhad.

Climate change can affect production of crops not only by altering rainfall amount and pattern but also by increasing temperature, which affects evapotranspiration. Higher CO_2 concentration can affect production of many crops, especially C_3 crops, by reduction of photorespiration and increment of photosynthesis rate (Amthor 2001). In addition, elevated CO_2 concentration reduces stomatal conductance and results in increasing water use efficiency (Lawlor and Mitchell 1991) so positive effects of higher CO_2 concentration on yield may be due to increase in photosynthesis, improvement of water use efficiency (which is very important in semiarid regions) or both (Amthor 2001).

However, other factors, including the effect of soil quality, presence of additional input like nitrogen or tropospheric ozone, can negate the fertilization influence of CO_2, as discussed in Tubiello and Ewert (2002). According to our results, it can be concluded that the yield chance in Birjand would be less than at the other locations due to climate change effects.

In general, scenario A2 represented higher wheat yield increases across all locations and time periods than scenario B1. This is mainly because scenario A2 is less concerned with rapid economic development and environmental issues while scenario B1 is based on achieving global solutions, environmental friendly technologies and has an interest in food quality and environmental issues. The difference of relative yield change between years as affected by the integrated effects of all factors showed more differences between 2020 and other time periods but less difference after this time in each location except under scenario A2 for Mashhad. In general, Mashhad showed the highest yield change considering integration of all evaluation factors. It seems Mashhad had maximum change of yield because of technology development. The effect of integrated factors caused a reduction in yield of 28 % in Bojnuord under scenario A2 in 2020 compared to the baseline time period (Table 8).

This may be due to a greater reduction in yield due to climate change (50 %, Table 8) and less of an increase from technology development (18 %, Table 8). Eyshi Rezaie and Bannayan (2012) reported a sharp decrease in wheat yield in the future climate in northeast of Iran but they did not consider the impacts of CO_2 concentration increase and technology development. Our results indicated an increasing yield of wheat in the future. Such an increase in food production may support a higher population, but it should be stressed that the estimation of production change was optimistic and did not consider the effect of pests, biotic and abiotic stresses and pollutants such as O_3 in the future.

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