Climate change impact on legumes’ water production function in the northeast of Iran

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ABSTRACT

Enhanced understanding of the climate impact on crops’ production is necessary to cope with expected climate variability and change. This study was conducted to find any robust association between crop yield and evapotranspiration using historical data (1986–2005) and subsequently employ the acquired relationship to project crop yield under future climate conditions for two agricultural centers in northeast Iran. Three legume crops of chickpea, lentil, and bean were selected in this study. The future precipitation and temperature data were projected by downscaling outputs of global climate model HadCM3 (A2 scenario) by LARS-WG stochastic weather generator. The data were downscaled for the baseline (1961–1990) and two time periods (2011–2030 and 2080–2099) as near and far future conditions. Projected temperature under A2 scenario showed increasing trend changed from 4 to 26% during the legumes’ growth period compared to baseline. In addition, projected annual precipitation change was between /C0 and 10% range under different time periods in contrast to baseline. There was a nonlinear relationship between crop yields and the seasonal values of crop evapotranspiration for all crops. The results showed that seasonal evapotranspiration would increase under climate change conditions across study locations. Crop yield would also increase for chickpea but not for lentil and bean for the far future in Sabzevar location compared to baseline. In conclusion, increasing the temperature and decreasing the precipitation may have a negative effect on legumes’ yield in northeast Iran, especially for far future conditions. Therefore, planning effective adaptation and mitigation strategies would be necessary for northeast Iran.

Key words | crop evapotranspiration, global warming, legumes, water demand

INTRODUCTION

Food security is a very critical issue especially in semi-arid conditions with expected climate change in the future. Crop evapotranspiration (ETc) is also a remarkable factor in determination of crop production. It seems that increasing the temperature and decreasing the precipitation under future climate change conditions may significantly influence the ETc (Sayari et al. 2013). Furthermore, there is a nonlinear relationship between ETc and crop yield (Zhang et al. 2004). Therefore, increasing the ETc under climate change would decrease the expected crop yield (Yu-Min et al. 2008). The relationship between evapotranspiration and crop yield production can provide helpful information as a basis to increase crop yield through better irrigation management and to estimate the required mitigation and adaptation requirements under future climate changes.

The ‘Production Function’ term was applied to describe any relationship between crop and irrigation water, temperature, precipitation, fertilizer, and energy (De Juan et al. 1996). Production function usually related to applied water to analyze production of total dry matter and/or marketable product (Y) for each crop in response to water (De Juan et al. 1996). Yield–seasonal evapotranspiration (ET) relations have been widely used for management purposes in water-deficient areas, such as Iran, as a guideline for...
irrigation. A number of studies have indicated a relationship between crop yield and the cumulative seasonal evapotranspiration. Linear relationship between crop yield and evapotranspiration production function has been reported for many crops at different locations (Beese et al. 1982; Orgaz et al. 1992). Various other studies have also reported a nonlinear relationship between crop yield and the ETc (Turk et al. 1980; Garrity et al. 1982; Evett et al. 1996).

French & Schultz (1984) studied the relationship between wheat yield and ETc in Australia and obtained wheat dry matter of 37 g ha⁻¹ mm⁻¹ of water use. Such evapotranspiration production functions are essential for improving water use efficiency and effective allocation of water resources among crops in a region (Zhang & Oweis 1999). Haxem & Heady (1978) demonstrated the application of similar production function to determine irrigation water requirement of crops.

Higher ET under global warming would negatively affect water resources. Increasing temperature would reduce soil moisture and therefore increase water use by irrigated crops (Charlton et al. 2006). Thus, the climate has a direct impact on crop production and food supply (Bannayan & Hoogenboom 2008; Bannayan & Sanjani 2011; Bannayan et al. 2011). The impact of climate change on crop yield has been widely studied by crop models and climate change scenarios (Bannayan et al. 2005; Challinor et al. 2005; Hussain & Mudasser 2007; Eyshi & Bannayan 2012). General circulation models (GCMs) are able to project future values of climate parameters such as precipitation, temperature, wind speed, and radiation, which are required in modeling crop production under climate change (Tao & Zhang 2010). These models are not applicable at the local and regional scales because of their coarse resolution. However, higher spatial resolution can be obtained by downscaling GCM outputs (Olesen et al. 2007).

Thomson et al. (2005) simulated crop yield under climate change scenarios, using three GCMs and also two levels of global mean temperature, by increasing +10 and +2.5 °C and two levels of CO₂ concentration (360 and 560 ppm). They showed that winter wheat yield increased under all scenarios from 8 to 37%. Xiong et al. (2010) studied climate change impacts on food production and showed that total water demand will increase by 20% and 18% for 2020 and 2040, respectively, in China. Lobell & Anser (2003) found the relationship between climatic data trend (temperature, precipitation, and solar radiation) and yields of corn and soybean in the USA for the period of 1988–1998. They found a 17% decrease in yield of both crops for each degree Celsius increase in temperature.

The main objectives of this study were: (1) the realization of projected climatic parameters under A2 scenario; (2) to compute the seasonal ETc by Penman–Monteith model for baseline (1961–1990), near future (2011–2030), and far future (2080–2099) for the northeast of Iran; and (3) to develop a robust relationship between the crop yield and seasonal evapotranspiration and the acquired relationship with historical data set and project the production of three major legume crops under future climate change.

MATERIALS AND METHODS

Study area and data

This study was performed for Razavi Khorasan province, which covers 117,710 km² (12,500 km² under cultivation) in the northeast of Iran (Figure 1). This region is located between 30° 21′–38˚ 17′ north latitude and 55° 28′–61˚ 20′ east longitude. The climatic pattern of this region follows semi-arid conditions. Mashhad and Sabzevar are the main agricultural centers of this province. The annual mean temperatures are 14.08 and 17.60 °C for Mashhad and Sabzevar, respectively. The total mean annual precipitation is between 192 m (Sabzevar) and 256 m (Mashhad) across the region. Water resources are mainly from ground water and also 14% from surface water; more than 86% of the total water consumption is used in the agricultural sector. Cereals, legumes, and vegetables are the dominant cultivated crops in the region. The main legumes cultivated in this region are chickpeas (Cicer arietinum L.), lentils (Lens culinaris L.), and beans (Phaseolus vulgaris L.). The average yield is 1.03 t ha⁻¹ for lentils, 1.25 t ha⁻¹ for chickpeas, and 1.0 t ha⁻¹ for beans (Khorasan Ministry of Agriculture 2008). The legumes are cultivated during early April and the growing season is between 120 and 130 days across the region (Khorasan Ministry of Agriculture 2008).

Daily climate data, including maximum and minimum temperatures (°C), sunshine duration (h), wind speed (ms), relative humidity (%), and precipitation (mm), were...
obtained for the period 1961–2005 from the Mashhad and Sabzevar climatological stations. Daily solar radiation was estimated from sunshine hours by applying the Angstrom–Prescott equation (Suehrcke 2000). The average yield of selected legumes for both locations was obtained from the province agricultural year book (Khorasan Ministry of Agriculture 2008).

Reference evapotranspiration

Potential evapotranspiration for each day during the growing season of legumes was calculated using the FAO (Food and Agricultural Organization of the United Nations, Rome, Italy) modified from the FAO Penman–Monteith equation (Allen et al. 1998) as follows:

\[
ET_0 = \frac{0.408\Delta (R_n - G) + \gamma (900/(T + 273)) \times \mu_2 \times (e_s - e_a)}{\Delta + \gamma (1 + 0.34 \times \mu_2)}
\]

where \(ET_0\) is the reference evapotranspiration (mm d\(^{-1}\)), \(\Delta\) is the slope of the vapor pressure curve, \(R_n\) is net radiation at the surface (MJ m\(^{-2}\) d\(^{-1}\)), \(G\) is the soil heat flux density (MJ m\(^{-2}\) d\(^{-1}\)), \(\gamma\) is the psychrometric constant, \(T\) is the mean daily air temperature at 2 m height, \(\mu_2\) is the wind speed at 2 m height, \(e_s\) is the saturated vapor pressure, and \(e_a\) is the actual vapor pressure (kPa). Daily values of total solar radiation at the earth’s surface \((R_s)\) were estimated using the procedure of Hargreaves & Samani (1982) and as subsequently modified by Allen (1997). Extraterrestrial solar radiation \((R_a)\) (MJ m\(^{-2}\) d\(^{-1}\)) was first calculated at the top of the earth’s atmosphere for each study day based on latitude, longitude, and the solar constant (Allen 1997). Then, \(R_s\) was calculated using the following equation:

\[
R_s = K_{Rs}(1 + 2.7 \times 10^{-15} \times \text{Alt}) \times (T_{\text{max}} - T_{\text{min}})0.5 \times R_a
\]

where Alt is the altitude (m) and \(K_{Rs}\) is an empirical coefficient set at 0.16 (Hargreaves & Samani 1982). \(T_{\text{max}}\) and \(T_{\text{min}}\)
are the maximum and minimum daily temperature, respectively. Clear-sky solar radiation \( R_{so} \) was calculated by the following equation (Allen et al. 1998):

\[
R_{so} = (0.75 + 2 \times 10^{-5}z)R_s
\]

(3)

where \( z \) is the station elevation above sea level (m). In addition, net shortwave radiation \( R_{ns} \) was obtained by the following formula (Allen et al. 1998):

\[
R_{ns} = (1 - \alpha)R_s
\]

(4)

in which \( \alpha \) is the albedo or the canopy reflection coefficient, which is 0.23 for the hypothetical grass reference crop. Net longwave radiation \( R_{nl} \), which is the rate of longwave energy emission, is proportional to the absolute temperature of the surface raised to the fourth power, calculated as follows (Allen et al. 1998):

\[
R_{nl} = \sigma \left( \frac{T_{\text{max,}h^t} + T_{\text{min,}h^t}}{2} \right) \times (0.34 - 0.14\sqrt{e_s}) \times \left( \frac{1.35}{R_{so}} - 0.35 \right)
\]

(5)

where \( \sigma \) is the Stefan–Boltzmann constant \((4.903 \times 10^{-8} \text{ MJ K}^{-1} \text{ m}^{-2} \text{ d}^{-1})\) and finally, net radiation at the surface \( R_{ns} \) obtained by the differences between \( R_{ns} \) and \( R_{nl} \).

**Vapor pressure deficit \((e_s - e_a)\)**

Calculation of vapor pressure deficit (VPD) was based on estimates of the differences between the average daily saturated water vapor pressure and the actual water vapor pressure. An estimation of actual vapor pressure can be obtained by assuming that dew point temperature \( T_{dew} \) is near the daily minimum temperature. In addition, saturated water vapor pressure was calculated by averaging of saturation vapor pressure at the minimum and maximum temperature \( e^0 \) using the following equation (Allen et al. 1998):

\[
\text{VPD} = \left( 0.611 \exp \left( \frac{17.27T_{dew}}{T_{dew} + 237.3} \right) \right) - \left( e^0(T_{\text{max}}) + e^0(T_{\text{min}}) \right) / 2
\]

(6)

**Crop evapotranspiration**

\( E_T \) was calculated from the computed \( E_{To} \) and crop coefficient \( (K_c) \).

\[
E_T = E_{To} \times K_c
\]

(7)

Crop development can be classified into four stages as initial stage, crop development stage, midseason stage, and late season stage. The length of each development stage was determined from local information, and the length of growing period of crop was considered based on farmers’ practice in the study area (Gontia & Tiwari 2009). Monthly crop coefficient \( (K_c) \) was estimated using the guidelines given in irrigation and drainage paper FAO-56 (Allen et al. 1998) for selected legume crops depending upon the stage of growth and adjusting by the following equations:

\[
K_{cmid} = K_{cmid(tab)} + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)] \times \left( \frac{h}{3} \right) \times 0.3
\]

(8)

\[
K_{cend} = K_{cend(tab)} + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)] \times \left( \frac{h}{3} \right) \times 0.3
\]

(9)

where \( K_{cmid(tab)} \) and \( K_{cend(tab)} \) are the tabulated values for \( K_{cmid} \) and \( K_{cend} \) respectively, in Table 12 of FAO 56 (Allen et al. 1998). \( RH_{min} \) is the mean value for daily minimum relative humidity during the midseason growth stage (%), for \( 20\% \leq RH_{min} \leq 80\% \), and \( h \) is mean plant height (m) during the midseason stage for \( 0.1 \text{ m} < h < 10 \text{ m} \) (Gontia & Tiwari 2009).

**Future climate projections**

Monthly time series of the climate variables simulated by the United Kingdom Met Office Hadley Centre (HadCM3) GCM (Mitchell et al. 1995) under emission scenarios (SRES-A2) was downscaled to daily time steps using the stochastic weather generator LARS-WG (Semenov & Stratonovitch 2010).

LARS-WG was calibrated using 31 years (1961–1990) observed daily weather data across study locations. The model parameters were then adjusted with the predicted changes in climatic mean and variability, derived from the
GCM output (Semenov 2009) to simulate daily time series for the three periods 1961–1990 (baseline), 2011–2030 (near future), and 2080–2099 (distant future). Based on this method, climate change information embedded in GCMs was employed to adjust the parameters used in LARS-WG that had previously been calibrated for the study locations by using observed daily weather data (Semenov & Brooks 1999). The uncertainty of the climate model was tested by root mean square error (RMSE) index as follows:

\[
\text{Normalized RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (P_i - O_i)^2}{n}} \times \frac{100}{O}
\]

where \(P_i\) and \(O_i\) indicate the simulated and observed data, respectively, \(O\) is the mean of observed data, and \(n\) is the number of observations. Finally, ET\(_c\) values were computed for climate projections for all study crops and both locations.

Yield estimation

Second order polynomial function was used for relating the crop yield to ET\(_c\) to estimation of crops yield as empirical model.

\[y = a + bx + cx^2\] (11)

The model was parameterized by average yield of 20 years (1986–2005) time series for all selected crops in the Mashhad location. Consequently, 16 years (1990–2005) of legumes’ average yield of the Sabzevar location was performed for testing the functions’ validity. At the final step, selected legume yields were estimated for different climate projections.

RESULTS

Models’ performance

Climate model

The accuracy of climatic variables’ simulations for the baseline period demonstrates the precision of downscaling method performance in climate change assessments (Viglizzo et al. 1997). In general, LARS-WG showed a high precision in predicting monthly maximum and minimum temperatures and precipitation with higher accuracy for the baseline period at Sabzevar (normalized RMSE = 3%, 1.3%, and 9% for maximum and minimum temperatures and precipitation, respectively) than Mashhad (normalized RMSE = 19%, 1.7%, and 11% for maximum and minimum temperatures and precipitation, respectively) (Figure 2).

Yield estimation model

The second order polynomial function showed a significant performance in estimation of chickpea \((R^2 = 0.62)\), lentil \((R^2 = 0.66)\), and bean \((R^2 = 0.61)\) yield for the Mashhad location in the parameterization process (Figure 3(a)). The legumes’ yield in the Sabzevar location was computed by performing the functions that were obtained from Mashhad for the model testing process. The results indicated that the functions and parameters would be able to reproduce the yield variability of chickpea \((R^2 = 0.52)\), lentil \((R^2 = 0.50)\), and bean \((R^2 = 0.58)\), but not absolute values (Figure 3(b)).

Future climatic conditions

The results of climate model projections showed the different trends in precipitation and mean temperature change under near (2011–2030) and far (2080–2099) future conditions (Figure 4). Annual precipitation sum values will increase by 10% and 13% in Mashhad (monthly range: +9 to +37%) and Sabzevar (monthly range: +1 to +49%) locations, respectively, under near future conditions compared to baseline (Figure 4(a)). However, annual precipitation sum values showed a −14% decrease for both Mashhad (monthly range: −47 to +14%) and Sabzevar (monthly range: −53 to +22%) locations in contrast to baseline under far future conditions (Figure 4(a)).

Climate projections showed an increasing trend in mean temperature under all time periods and in both locations (Figure 4(b)). Annual mean temperature will slightly increase (+5%) in Mashhad (monthly range: +4 to
and Sabzevar (monthly range: +4 to +18%) locations under near future conditions compared to baseline (Figure 4(b)). On the other hand, annual mean temperature trend indicated a sharp increase under far future conditions in both locations (+26%) compared to baseline (Figure 4(b)).
Estimated yield under future climate

Chickpea

The projected climate data for this region were used for estimating the yield of legume crops based on obtained functions under future climate change conditions. The chickpea yield and ET<sub>c</sub> did not show a significant change (−1%) in the near future (2011–2030) compared to baseline in both locations (Figure 5(a)). However, chickpea yield and ET<sub>c</sub> will slightly increase (+6%) in Mashhad location under far future (2080–2099) conditions in contrast to baseline, but this increase was not monitored in Sabzevar (Figure 5(a)).
The results of projected yield of lentils showed that there was no difference between baseline and different time periods, although ETc values showed a +4% increase under far future conditions compared to baseline (Figure 5(b)). Projected yield and ETc of lentils did not illustrate a remarkable change during the near future in Sabzevar location (Figure 5(b)) either. On the other hand, projected yield of lentils showed a 10% decrease under far future conditions in contrast to baseline for Sabzevar (Figure 5(b)).

**Bean**

There was no remarkable change between projected bean yield and ETc for both study locations during near future conditions (Figure 5(c)). Nevertheless, the projected yield did not show the same trend in the study locations. Projected yield of beans showed a minor increase (+4%)
Figure 5 | Estimated yield (kg ha\(^{-1}\)) and cumulative seasonal ETc (mm) of chickpea (a), lentil (b), and bean (c) under baseline, near (2011–2030), and far (2080–2099) future conditions in study locations.
under far future conditions in Mashhad. However, bean yield indicated an 8% decline under far future conditions in Sabzevar compared to baseline (Figure 5(c)).

DISCUSSION

Increasing demand for water along with expansion of both agricultural and industrial sectors has resulted in water scarcity almost every year in many parts of the world. Droughts occur in all climate zones including high and low rainfall locations. Drought, depending on its intensity, could impact many sectors of society and might also reach beyond areas that experience drought. These impacts have been particularly harsh in developing countries where both the human and economic loss can be shocking and financially limited. Farmers have tried to prevent or mitigate the impact of drought on agricultural production by increasing the diversity of cultivated crops, cultivation of resistant crop varieties, or other management factors (Lashkari et al. 2012). Projections of climate models have indicated that aridity in the 21st century will increase over most parts of Africa, southern Europe, the Middle East, parts of America, Australia, and East Asia. Such an increase in drought frequency would have major implications for natural resource management, water security planning, water demand management strategies, and drought relief payments. Based on our results, the mean temperature showed an increasing trend for all time periods and both locations under A2 scenario. The high temperature reduces the yield and quality of many crops, particularly cereal and food grains (Bannayan et al. 2011). However, annual precipitation sum values indicated a slight increase under near future (2011–2030) but declines (−14%) during the far future (2080–2090). The SRES-A2 scenario is one of the most extreme scenarios, with global carbon emissions rising from about 10 Gt at present to over 25 Gt in 2100 (medium to high carbon emissions) (Prudhomme et al. 2010). This emission scenario is commonly used for ‘business as usual’ impact studies, projecting a 3 °C increase in global surface air temperature by 2100 (Donner et al. 2005).

Legumes’ water production function showed a nonlinear trend in the study region. Based on the fitted functions for legume crops, increasing the ETc enhances the crops’ yield until an ETc threshold; however, the crops’ yield showed a levelling-off trend beyond this threshold. It seems that increasing the ETc values to more than the threshold declined the yield, especially under far future conditions in Sabzevar, which is drier and warmer than Mashhad.

In addition, the results of our study showed that cumulative ETc would increase under climate change scenarios for selected crops in the study area. It seems increasing the temperature under climate change conditions raises the ETc values. Tao et al. (2008) used Monte Carlo analysis to simulate rice yield under baseline (1961–1990) and future climate change conditions. They found significant shortening in growing season length that subsequently reduced the rice yield from 6 to 18% by increasing 1 °C, 13 to 40% by increasing 2 °C, and 23 to 40% by increasing 3 °C of mean temperature. Al-Jamal et al. (2000) computed the crop water production function for onion crops and found a direct relationship between ETc and crop yield. In conclusion, estimation of crop yield based on empirical models could not simulate the absolute values of crop yields. It should be also mentioned that in addition to climate change, technology development and CO2 concentration also play vital roles in determination of agricultural production in the future. However, focus on combination of these factors, especially on technology development, has not yet been adequately considered. Results presented in this study provide insights on the magnitude of the climate change potential impacts on legumes’ crop yield.

REFERENCES


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