Assessing the response of dryland barley yield to climate variability in semi-arid regions, Iran: Postprint

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Abstract

Precipitation and temperature are the most abiotic factors that greatly impact the yield of crop, particularly in dryland. Barley, as the main cereal is predominantly cultivated in dryland and the livelihood of smallholders depends on the production of this crop, particularly in arid and semi-arid regions. This study aimed to investigate the response of the grain yield of dryland barley to temperature and precipitation variations at annual, seasonal and monthly scales in seven counties of East and West Azerbaijan provinces in northwestern Iran during 1991–2010. Humidity index (HI) was calculated and its relationship with dryland barley yield was evaluated at annual and monthly scales. The results showed that the minimum, maximum and mean temperatures increased by 0.19°C/a, 0.11°C/a and 0.10°C/a, respectively, while annual precipitation decreased by 0.80 mm/a during 1991–2010. Climate in study area has become drier by 0.22/a in annual HI during the study period. Negative effects of increasing temperature on the grain yield of dryland barley were more severe than the positive effects of increasing precipitation. Besides, weather variations in April and May were related more to the grain yield of dryland barley than those in other months. The grain yield of dryland barley was more drastically affected by the variation of annual minimum temperature comparing with other weather variables. Furthermore, our findings illustrated that the grain yield of dryland barley increased by 0.01 t/hm2 for each unit increase in annual HI during 1991–2010. Finally, any increase in the monthly HI led to crop yield improvement in the study area, particularly in the drier counties, i.e., Myaneh, Tabriz and Khoy in Iran.

Full Text

Preamble

Assessing the Response of Dryland Barley Yield to Climate Variability in Semi-Arid Regions, Iran

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Abstract

Precipitation and temperature are the most critical abiotic factors that greatly impact crop yield, particularly in dryland systems. Barley, as a main cereal crop, is predominantly cultivated in dryland areas where the livelihoods of smallholders depend on its production, especially in arid and semi-arid regions. This study investigated the response of dryland barley grain yield to temperature and precipitation variations at annual, seasonal, and monthly scales across seven counties in East and West Azerbaijan provinces in northwestern Iran during 1991–2010. The humidity index (HI) was calculated and its relationship with dryland barley yield was evaluated at annual and monthly scales. The results showed that minimum, maximum, and mean temperatures increased by 0.19°C/a, 0.11°C/a, and 0.10°C/a, respectively, while annual precipitation decreased by 0.80 mm/a during the study period. The climate in the study area became drier, as evidenced by a 0.22/a decline in annual HI. The negative effects of increasing temperature on dryland barley grain yield were more severe than the positive effects of increasing precipitation. Weather variations in April and May were more closely related to barley grain yield than in other months. Among all weather variables, variations in annual minimum temperature most drastically affected barley grain yield. Furthermore, our findings illustrated that dryland barley grain yield increased by 0.01 t/hm^2 for each unit increase in annual HI during 1991–2010. Finally, any increase in monthly HI led to crop yield improvement in the study area, particularly in drier counties such as Myaneh, Tabriz, and Khoy in Iran.

Keywords: humidity index; crop yield; spatiotemporal variation; temperature; precipitation

1 Introduction

Barley (*Hordeum vulgare* L.) is one of the oldest cultivated crops in the world, growing at different latitudes from near the equator to 70° North (Dawson et al., 2015). Barley is naturally drought-tolerant (Cammarano, 2019) and resistant to hot summers and cold winters with high variability in precipitation and temperature (Brisson et al., 2010). Barley also makes a significant contribution to international trade, and inadequate production of this crop is considered one of the main factors contributing to global food scarcity (Fellmann et al., 2014; d' Amour et al., 2016). Accordingly, the livelihoods of smallholders depend on barley production at national and regional scales, particularly in arid and semi-arid regions (Macdonald and Hall, 1980; Qader et al., 2018).

Arid and semi-arid regions have undergone changes including increases in temperature and decreases in precipitation at annual, seasonal, and monthly scales (Karimi et al., 2018; Rahimi et al., 2019; Senapati et al., 2019; Shirmohammadi et al., 2020; Kheiri et al., 2021). According to recent reports, these climate changes have significantly caused negative effects on crop production (Chen et al., 2016; Bathiany et al., 2018; Bisbis et al., 2018). In this context, Schierhorn et al. (2020) investigated the impacts of climate change on wheat and barley yields in Kazakhstan and found that observed climate change led to yield reductions of 1.9% and 4.8%, respectively. Hatfield et al. (2011) argued that cereal grain yields decreased between 4.1% and 10.0% with a 1°C increase in seasonal average temperature. Cammarano et al. (2019) evaluated the impacts of climate change on barley yield in the Mediterranean Basin and found that increasing air temperatures by 7%-18% and decreasing precipitation by 14%-21% led to a 27% grain yield reduction in dryland. Asseng et al. (2011) found that a 2°C increase in average temperature during the growing season reduced wheat yield by 50%. Xiao et al. (2016) reported that rainfed wheat yield decreased significantly by 19.5%, 33.6%, and 53.1% for 10%, 20%, and 30% decreases in precipitation, respectively. Identifying crop yield sensitivity to climate change is critically important for adopting effective adaptive strategies (Zhao et al., 2017) that improve yield potential.

Arid and semi-arid regions cover an area of about 1.75$\times10^{6}$ km^2 in Iran. Temperature varies from -20°C to 50°C, while annual precipitation ranges from less than 50 to more than 1000 mm (Mesgaran et al., 2017). Iran is predominantly an agricultural country with approximately 37$\times10^{6}$ hm^2 of arable land (Karimi et al., 2018). Cereals are the most important crops cultivated in Iran' s arable lands, and barley is among the main cereals predominantly grown in drylands. Barley provides both animal and human food, and local farmers' livelihoods are strongly influenced by its production. Barley is the second major dryland crop in Iran in terms of cropping area, contributing to almost 18% of total dryland agricultural products (Ministry of Agriculture-Jihad (MAJ), 2018). Approximately 60% of this area is dryland where barley production completely depends on precipitation amounts during the crop growing season.

East Azerbaijan and West Azerbaijan, located in northwestern Iran, are two main provinces for barley production, together accounting for 10% of Iran' s total dryland barley production (MAJ, 2018). The present study aims to: (1) assess temperature and precipitation variability time series in East and West Azerbaijan provinces during 1991-2010; and (2) investigate the relationship between temperature and precipitation variability and dryland barley yield. Accordingly, this study seeks to answer the following research questions: Which variables (precipitation and/or temperature) changed more drastically during the study period? Which areas experienced greater changes in dryland barley grain yield? Which climatic variables affected dryland barley grain yield? When are the most critical times for determining dryland barley grain yield?

2.1 Study Area

The study area comprises two northwestern provinces of Iran: East Azerbaijan and West Azerbaijan [Figure 1: see original paper]. East Azerbaijan Province covers 45,481 km^2, representing approximately 2.8% of Iran' s total area, with mean annual precipitation of 288.9 mm and annual minimum, maximum, and mean temperatures of 6.9°C, 18.0°C, and 12.4°C, respectively. West Azerbaijan Province covers 37,059 km^2, representing approximately 2.3% of Iran's total area, with mean annual precipitation of 341.0 mm and annual minimum, maximum, and mean temperatures of 5.4°C, 17.6°C, and 11.5°C, respectively. The study focuses on seven counties: Ahar, Tabriz, Maragheh, Myaneh, Urmia, Khoy, and Makou [Figure 1: see original paper].

2.2 Weather Data

Weather data were collected from the Iran Meteorological Organization, including annual minimum, maximum, and mean temperatures and total precipitation for the period 1991-2010. Before analysis, outlier detection and normality tests were applied to exclude outliers and evaluate data homogeneity. All data were averaged to obtain corresponding values at annual, seasonal, and monthly scales.

2.3 Crop Yield Data

Dryland barley yield data for 1991-2010 were collected from the Ministry of Agriculture-Jihad (MAJ) of Iran. Barley sowing dates depend on fall precipitation, while harvesting depends on air temperature in late spring or early summer, making barley production entirely dependent on local climate. To determine the growing season in each province, meetings were held with agronomists from East and West Azerbaijan Agricultural Organizations. The growing seasons in both provinces overlapped considerably, with the season beginning in July and ending in October. It should be noted that this study investigates weather variable impacts on dryland barley grain yield during the crop growing season from July to October, so correlations between weather variables and crop yield were not analyzed for August to September.

Since the objective was to investigate climate factor (temperature and precipitation) effects on dryland barley grain yield, non-climatic factors such as crop genetics and technical improvements were eliminated using the Double Exponential Smoothing (DES) method (Joseph and LaViola, 2003). This method calculates crop yield anomalies as the difference between annual yield and the long-term average yield [Figure 2: see original paper]. Compared to other approaches, DES gives relatively more weight to new observations than older ones (Bannayan et al., 2010). While this method does not entirely eliminate non-climatic factor impacts across years, it represents the best possible approach for excluding other factor effects (Kheiri et al., 2017).

2.4 Humidity Index (HI)

This study used the de Martonne equation to quantify HI for all studied counties (Bannayan et al., 2010; Zarghami et al., 2011):

$$\mathrm{HI} = \frac{P}{T + 10}$$

where P is mean annual/monthly precipitation (mm) and T is annual/monthly mean temperature (°C). When HI falls between 10 and 20, the climate is classified as semi-arid; HI less than 10 indicates arid climate (Croitoru et al., 2013).

2.5 Statistical Analysis

Simple linear regression was used to investigate variation in each variable at annual, seasonal, and monthly scales during 1991–2010. Pearson correlation coefficients were calculated at annual, seasonal, and monthly scales to examine relationships between weather variables, HI, and dryland barley grain yield. Simple linear regression and Pearson correlation were computed using Minitab software. Spatial analysis of weather variables, HI, and barley yield was performed using ArcGIS 10.4 (ESRI, 2016) with the Inverse Distance Weighting (IDW) interpolation method. IDW is a deterministic spatial interpolation model popular among geographers and geoscientists for interpolating climate variables (Chen and Liu, 2012; Yang et al., 2015; Jeong et al., 2020). Its main advantages include calculation simplicity, ease of understanding, and high output efficiency (Maleika, 2020).

3.1 Spatiotemporal Variations of Barley Grain Yield, Climate Variables, and Annual HI

Spatial distribution analysis revealed that the highest barley grain yields (>0.80 t/hm^2) occurred in Urmia and Ahar counties, while the lowest yields (<0.70 t/hm^2) were observed in Khoy and Tabriz counties [Figure 3a: see original paper]. On average, dryland barley grain yield showed an increasing trend of 0.01 t/(hm^2 · a) across the study area during 1991–2010 . Specifically, dryland barley grain yield significantly increased by 0.01 and 0.03 t/(hm^2 · a) in Ahar and Urmia counties, respectively .

Substantial variability characterized the spatial distribution of weather variables across the study area [Figure 3: see original paper]. Annual minimum, maximum, and mean temperature distributions showed that Ahar, Urmia, and Makou counties were cooler than others, while Myaneh County was the hottest during 1991–2010 [FIGURE:3b–d]. Total precipitation ranged from 255 to 310 mm, with Tabriz and Khoy counties receiving the lowest amounts and Urmia and Maragheh receiving the highest [Figure 3e: see original paper]. Generally, East Azerbaijan experienced higher air temperatures and lower precipitation than West Azerbaijan during 1991–2010 [Figure 3: see original paper].

Annual minimum, maximum, and mean temperatures increased by 0.19°C/a, 0.11°C/a, and 0.10°C/a, respectively, during 1991–2010 . The strongest temperature variations occurred in Myaneh County . Total precipitation decreased by 0.80 mm/a on average, with the most substantial decrease of 5.48 mm/a in Myaneh County .

Based on annual HI distribution, all studied counties were classified as semi-arid climate (Eq. 1; [Figure 3f: see original paper]). However, Khoy, Tabriz, and Myaneh counties with annual HI $<$ 13 were drier, while Urmia County with annual HI $>$ 17 was wetter than others [Figure 3f: see original paper]. Regression analysis indicated that the study area climate became drier, with annual HI decreasing by 0.22/a during 1991–2010 . Annual HI showed a more significant descending trend in East Azerbaijan than in West Azerbaijan, with the most significant reduction detected in Myaneh County (0.40 per year) .

3.2 Relationship Between Weather Variables and Barley Grain Yield at Annual, Seasonal, and Monthly Scales

At the annual scale, correlation analysis revealed negative impacts of increasing air temperature on dryland barley grain yield in some counties . Specifically, grain yield significantly decreased with increasing annual minimum temperature in Makou (r = -0.54). Grain yield also significantly decreased with increasing annual maximum temperature in Urmia and Makou (r = -0.53 and r = -0.54, respectively). Additionally, a negative relationship existed between annual mean temperature and grain yield in Makou (r = -0.54) . However, no significant correlation was found between precipitation and grain yield at the annual scale .

At the seasonal scale, significantly negative relationships were observed between winter minimum, maximum, and mean temperatures and barley grain yield in Myaneh (r = -0.62, r = -0.63, and r = -0.63, respectively) . In spring, increasing maximum temperature significantly decreased dryland barley grain yield in Khoy (r = -0.53) . The relationship between spring precipitation and dryland barley grain yield was statistically significant in Myaneh (r = 0.52). Moreover, increasing minimum, maximum, and mean temperatures in spring negatively impacted dryland barley grain yield in Myaneh (r = -0.72, r = -0.59, and r = -0.65, respectively) . In fall, increasing minimum and mean temperatures significantly decreased dryland barley grain yield in Maragheh (r = -0.58 and r = -0.54, respectively) . Although remarkable relationships existed between weather variables and grain yield in other counties at the seasonal scale, these were not statistically significant .

At the monthly scale, correlation analysis revealed several significant relationships . In January, minimum and mean temperatures showed significantly negative relationships with dryland barley grain yield in Makou (r = -0.54 and r = -0.53, respectively). However, this result may not accurately describe the correlation in Makou, which experiences very cold, freezing winters where frost damage is a major stressor for barley cultivation. In such conditions, temperature increases could have positive impacts on crop yield. In April, minimum, maximum, and mean temperatures were negatively related to dryland barley grain yield in Myaneh (r = -0.54, r = -0.56, and r = -0.59, respectively), while precipitation showed a significant positive relationship (r = 0.55). In May, minimum, maximum, and mean temperatures showed significantly negative relationships with grain yield in Ahar (r = -0.55, r = -0.52, and r = -0.58, respectively). Increased minimum and mean temperatures in May also significantly decreased grain yield in Tabriz (r = -0.60 and r = -0.54), Myaneh (r = -0.57 and r = -0.54), and Makou (r = -0.76 and r = -0.58) . In June, minimum temperature showed a significant negative correlation with grain yield in Myaneh (r = -0.61). In December, increasing mean temperature significantly decreased grain yield in Myaneh (r = -0.57), while precipitation showed a significant positive relationship with grain yield in Tabriz (r = 0.60) .

4.1 Spatiotemporal Relationships of Barley Grain Yield, Weather Variables, and Annual HI

The findings showed considerable similarities between spatial distributions of annual HI and total precipitation, revealing precipitation' s dominant contribution to annual HI [FIGURE:3e and f]. Strong similarities were also observed between annual HI and barley grain yield [FIGURE:3a and f], suggesting that higher annual HI corresponds to greater grain yield. These findings align with Bannayan et al. (2010) and Kheiri et al. (2017), who reported that annual HI closely follows the spatial distribution of total precipitation and significantly influences wheat and barley yield distributions, emphasizing HI' s undeniable role in determining crop yield.

The study area climate became drier (temperature increased and precipitation decreased), particularly in drier areas such as Myaneh and Khoy, during 1991-2010 . These findings confirm Tabari et al. (2014), who reported that northwest Iran's climate became significantly drier based on the de Martonne aridity index during 1966-2005.

4.2 Assessment of Barley Grain Yield Response to Weather Variables at Annual, Seasonal, and Monthly Scales

At the annual scale, dryland barley grain yield was negatively affected by increasing air temperature. Higher temperatures accelerate phenological development and shorten growth duration, reducing light interception, photosynthesis rates, and leaf area, or even causing leaf withering, consequently reducing biomass and grain yield (Asseng et al., 2015). Bannayan et al. (2010) reported that air temperature was a determining factor for dryland wheat and barley grain yields in semi-arid regions of Khorasan Province, northeastern Iran. Alexandrov and Hoogenboom (2001), Padakandla (2016), and Kheiri et al. (2021) similarly reported that increased ambient temperatures shorten crop growth duration and reduce final grain yield.

At seasonal and monthly scales, two main findings emerged: (1) the negative effects of increasing temperature on dryland barley grain yield were more severe and significant than the positive effects of increasing precipitation, particularly in drier areas such as Myaneh; and (2) weather variations in spring were more closely related to dryland barley grain yield than in other seasons. These findings are supported by monthly-scale relationships where April and May were identified as the most important months with stronger, more substantial relationships between weather variations and grain yield. The effects of seasonal or monthly weather variations on grain yield primarily reflect different hydrothermal demands during various growing seasons. When hydrothermal conditions align with crop growth requirements, grain yield increases, and vice versa. Proper grain yield depends on material accumulation during the growing season and dry matter translocation to grain during the reproductive phase. Since barley' s reproductive phase begins in spring (approximately April-May in the study area), temperature increases can advance leaf senescence, decrease radiation interception by the crop canopy, and reduce grain yield. Siebert and Ewert (2014) demonstrated that high temperatures during sensitive growth periods such as grain-filling can disrupt pollination, reduce grain number, and dramatically decrease final yield. Rosenzweig et al. (1996) indicated that higher late-spring temperatures during grain-filling increase maintenance respiration, reduce CO_2 assimilation rates, and negatively impact yield. Similar findings have been reported elsewhere (Tewolde et al., 2006; Tao et al., 2015; Chen et al., 2017; Kheiri et al., 2017; Karimi et al., 2018). Previous studies suggest adaptation strategies such as changing sowing dates and cultivars to mitigate negative temperature effects (Plaut et al., 2004; Ugarte et al., 2007; Kheiri et al., 2021).

The findings also demonstrated positive impacts of spring precipitation (e.g., in April) on dryland barley grain yield in drier areas such as Myaneh. Adequate precipitation during the reproductive phase can delay leaf senescence by alleviating terminal drought—the most prominent concern in dryland production that causes chlorophyll and membrane breakdown and leaf chlorosis (Farooq et al., 2014)—thus increasing grain yield (Lobell et al., 2011; Nio et al., 2011; Tao et al., 2017). The relationships between crop yield and weather variables could be attributed to minimum temperature' s negative impacts , consistent with Lizaso et al. (2018), Xiao et al. (2018), and Kheiri et al. (2021), who found that warmer night temperatures enhance maintenance respiration at the expense of crop growth and grain yield.

4.3 Assessment of Barley Grain Yield Response to HI at Annual and Monthly Scales

As shown in Figure 4, grain yield responded positively to increased annual HI across all study areas, confirming strong similarities between annual HI and grain yield. These results demonstrate that annual HI can explain temporal and spatial variations in rainfed barley, making it an appropriate and simple indicator for determining suitable areas for growing dryland crops such as barley based on climate conditions.

The findings also showed that any increase in monthly HI led to crop yield improvement in the study area, particularly in drier counties such as Myaneh, Tabriz, and Khoy. The correlation between dryland barley grain yield and monthly HI was stronger during the latter growing season (April–July) than the former (October-March). Local farmers' experience indicates that the most crucial barley growth and development stages occur during the latter growing season, when drought stress affects crop yield more than in the former season. Narasimhan and Srinivasan (2005) found strong relationships between drought indices and wheat yield during the growing season, emphasizing that adequate soil moisture is critical for final grain yield. Bannayan et al. (2010) divided barley and wheat growing seasons into wet (early to middle) and dry (end) periods, finding stronger HI–crop relationships in the dry season and confirming that higher monthly HI during the dry season is more effective for crop yield. Overall, HI serves as an appropriate index for describing spatiotemporal variability in dryland barley grain yield across different counties in Iran.

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5 Conclusions

This study investigated dryland barley grain yield response to temperature and precipitation variations at annual, seasonal, and monthly scales. The findings showed that the study area climate became drier, particularly in drier areas such as Myaneh and Khoy, during 1991-2010. The negative effects of increasing temperature on dryland barley grain yield were more severe and significant than the positive effects of increasing precipitation, especially in drier areas. Weather variations in spring (April and May) were more closely linked to grain yield than in other periods. Among weather variables, variations in annual minimum temperature had the greatest impact on grain yield. Furthermore, grain yield distribution was impressively influenced by spatial distribution of annual HI, highlighting HI' s undeniable role in determining crop yield. Overall, any increase in monthly HI led to grain yield improvement in the study area, particularly in drier counties. The main implication of these findings is improved understanding of crop-climate relationships during the growing season, which can be applied to regional yield forecasting and projections of climate variability impacts on dryland crop yields.

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