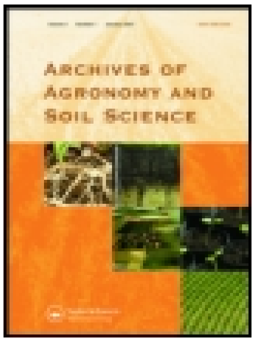

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Evaluation of forage maize yield gap using an integrated crop simulation model-satellite imagery method (Case study: four watershed basins in Golestan Province)

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ABSTRACT

The yield gap provides a guide for prioritization of crop management options (such as optimized sowing date, seeding rate, irrigation schedule, soil fertility, fertilizer application, weed and pest control) in a studied area. This study aimed to determine the maize yield gap in four major watersheds in Golestan Province, Iran, using an integrated crop simulation model-satellite imagery method. The actual yield estimated by the NDVI (as the selected index) was between 8.89 and 20.40 t ha^{-1}, while the potential yield is between 19.03 and 22.35 t ha^{-1}. About 91.76% of the studied area had a yield less than 85% of the potential yield. The lowest actual yield was in the south, southeast, and north of the study area. The yield gap was estimated between 0 to 11.76 t ha^{-1} and 66.66% of maize farms yield gap was between 3.5 to 5.5 t ha^{-1}. The yield gap fraction changed between 0 and 0.57. The results showed that soil-dependent variables, slope, and fluctuation in farm management factors (plant density, planting, irrigation, and various methods of weed control) caused the yield gap. High yield gap indicates that there is an opportunity to increase production through managerial optimization or excluding maize from cropping patterns.

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GIS; maize; NDVI; solar radiation; yield gap

Introduction

Various features of maize, especially its ability to adapt to different climatic conditions and its use in different forms, have led to a growing demand for its consumption (Nour-Mohamadi et al. 1997; Khajehpour 2013). Thus, maize, with a cultivated area of 1,714,817 ha, ranks second in the world after wheat, which has been in the first place in terms of production (883,460,240 ton of grain and 9,111,763 ton of fodder) in recent years (Khajehpour 2013). Iran has a cultivated area of 166,173 ha for grain maize and of 243,378 ha for forage maize (with average yields of 7034 kg ha^{-1} and 45,933 kg ha^{-1}, respectively) (Information and Communication Technology Center 2016), but the country has so far failed to provide its own domestic needs and is among the top maize importers (Khajehpour 2013).

Increasing the yield of crops has been taken into account due to a high global demand for food caused by population growth and higher incomes (Van Ittersum et al. 2013; Davis et al. 2017). Increased yield with this method is affected by various factors such as plant characteristics and environmental

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and managerial elements. The individual contribution of each of these cases varies strongly due to the characteristics of production across global regions, which may cause deviation from the true potential of agricultural production (yield gap) (Neumann et al. 2010). Yield gap is the difference between the actual yield by the farmers and potential yield expected. By definition, potential yield is the yield obtained for a single variety in the absence of limiting and reducing factors of production. Limiting factors are factors such as water and nutrients that should be supplied as sources to the plant. Therefore, potential yield is considered the maximum yield, which could be obtained by a crop in given environments (Evans and Fischer 1999). The actual yield is achieved when, in addition to determinant factors such as solar radiation, temperature, and atmospheric carbon dioxide concentration, other factors such as water and nutrient shortage, weeds, diseases, pests and environmental stress also affect yield (Cassman et al. 2003); therefore, actual yield could be known as an indicator of the current state of soils and climate, average skills of the farmers, and farmer's average use of technologies (FAO and DWFI 2015). Determination of yield gap will be essential to identify the possibility of yield improvement in the near future and to ensure food security (Ray et al. 2012; Meng et al. 2013). In order to calculate the yield gap, its causes, including soil quality, weather conditions, changes in plant genetics, and management practices, should be identified. Furthermore, the yield limitation quality caused by these factors should be determined and quantified. Ultimately, the yield gap should be reduced through effective management and operational policies (Lobell et al. 2009; Liu et al. 2012; Mueller et al. 2012; Li et al. 2014).

Yield gap has been investigated in different ways such as modelling (Grassini et al. 2011; Affholder et al. 2013; Folberth et al. 2013; Lv et al. 2015), satellite-based methods (Zhao et al. 2016; Zhao and Lobell 2017), combined geographic information system (GIS) and simulation models (Wu et al. 2008; Liu et al. 2012; Sanjani et al. 2012), combined GIS, simulation models and satellite imagery (Schulthess et al. 2013; Lobell et al. 2015; Zhao et al. 2015; Farmaha et al. 2016), meta-analytical methods, regression models and modified models (Sileshi et al. 2010) for maize, and analysis of the boundary line for wheat (Hajjarpour et al. 2015), maize, and rice (Neumann et al. 2010). Sanjani et al. (2012) examined the potential yield and the yield gap of maize using CSM-CERES-Maize model by GIS and reported the potential yield and yield gap for Northern, Razavi and Southern of Khorasan provinces to be 16.4, 14.1, and 10.2 t ha^{-1} and 9.7, 8.61, and 6.28 t ha^{-1}, respectively. Using the Hybrid-Maize model, Meng et al. (2013) estimated maize yield gaps to be 6 t ha^{-1} and 8.6 t ha^{-1} for irrigated and rain-fed conditions, respectively, and reported farmers' yields to be between 48 and 56% of the potential yield in China. Maize yield gaps were reported to be between 30 and 50% in Nebraska, USA (Farmaha et al. 2016) and 64% on a global scale (Mueller et al. 2012). Liu et al. (2012) noted a maize yield gap between 9 and 75% of the potential yield in north-eastern China and attributed the changes to climatic conditions and agricultural management practices. Neumann et al. (2010) calculated a maize yield gap of 0–9 t ha^{-1} on a global scale and found a significant correlation between the yield gap and irrigation, availability, market demand, agricultural labor, and slope. The maize yield gap was also estimated by other researchers (Grassini et al. 2011; Van Wart et al. 2013; Kassie et al. 2014; Pasuquin et al. 2014; Lobell et al. 2015).

Because of the human needs for meat products, fodder supply for increasing livestock production is a critical issue that can be fulfilled by identification of the yield gap in forage-producing plants such as maize and through trying to reduce the gap.

The average yield of maize forage in Golestan province is very low compared to expected average. Forage production reaches around 85 t ha^{-1} in some Iranian provinces, while the maximum forage production reported in Golestan province has been 36 t ha^{-1} (the average yield of the entire country is about 50 t ha^{-1}). This difference indicates the necessity of checking the yield gap of maize forage in Golestan province, which is affected by climatic changes, instability of soil conditions, lack of proper managements, farmers low literacy, drought stresses in recent years, water shortage, lack of appropriate cultivars and pests and diseases as the main factors that reduce forage yield.

Studies on the yield gap have mostly focused on maize in most of the world, while the silage plant provides plenty of livestock rations. This means that few studies have been done to evaluate the yield of maize forage and major studies on the yield gap of maize have focused on grain yield. For instance, Srivastava et al. (2017) studied the yield of maize in Ghana, with a grain yield gap of 8.8 to 10 t ha^{-1} and biomass yield gap of 14.8 to 17.1 t ha^{-1}, respectively. They reported that the average grain yield and biomass yield were 17% and 13% of simulated water limited yield, respectively. Therefore, this study was carried out with the aim to evaluate the forage maize yield gap at four important watersheds in Golestan province. The CERES-Maize model and techniques of remote sensing and GIS were used as systemic approaches to calculate the regional yield factor. Also, the yield gap fraction was analyzed in the cultivated lands.

Materials and methods

Study area

The research was conducted on a maize variety (Cross 704) at four basins of Qaresoo, Qarnabad, Mohammadabad, and Zaringol in Golestan province (36°35′ to 37°14′ north and 54°20′ to 55°11′ east). The area of this study covers 199,230 ha of arable lands, with an altitude ranging from −33 to 3666 m, an annual precipitation of 345.3 – 620.6 mm, and minimum and maximum temperatures of −4.2°C and 46°C, respectively. Maize is usually cultivated in the spring (for grain) and summer (for fodder) in the province and the summer irrigated form is generally cultivated after barley, canola, and, in particular, wheat (Figure 1).

Detection of maize fields by supervised classification method

In order to detect maize fields from other agricultural uses, at first, the 1 to 7 bands of LandSat8 satellite with the spatial resolution of 30 m were combined in the ERDAS IMAGING 2014 environment and the image contrast improved with the help of band 8 (with a spatial resolution of 15 meters) for better detection of the features using resolution merge function. For the final accuracy evaluation of detected crops, 82, 61, 32, 16, and 63 recorded ground control points (coordinated with GPS, Garmin 550 model), related to unplanted lands, maize fields, rice fields, tobacco fields and soybean fields, respectively, were used. Then, classification was done using supervised classification method in the ERDAS IMAGING 14 environment.

Calculation of radiation reaching the maize fields and potential yield

The amount of transmitted radiation during the growing season of maize (July 18 to October 13 2015) in the study area was estimated using the Area Solar Radiation function in the GIS environment (ARCGIS 10.3 software). The function was run using a digital elevation model (DEM) layer (50 m × 50 m) and by the regional radiation parameters including the diffuse model type, diffuse proportion, and the transmittivity fraction for Golestan province. DEM was provided from the Iran National Cartographic Center (http://ncc.org.ir). Regional radiation parameters were estimated based on the amount of radiation reaching the earth at all the study stations (nine weather stations and three evaporation stations). The level of radiation was calculated in the GIS environment for the entire province. To extract the coefficients of the function, the coefficients calculated by Badsar et al. (2017) were considered and the accuracy of the outputs was compared with the amount of radiation recorded at the stations. Then the coefficients were calibrated to reduce the error. These coefficients were determined for the 89-day growing period of maize in the studied area as diffuse proportion of 0.46 and transmittivity coefficient of 0.53. Additionally, diffuse model type was uniform. The amount of irradiation was estimated during the growth period of forage maize as accumulated radiation intensity. Layer was provided by a 50 m × 50 m spatial resolution.

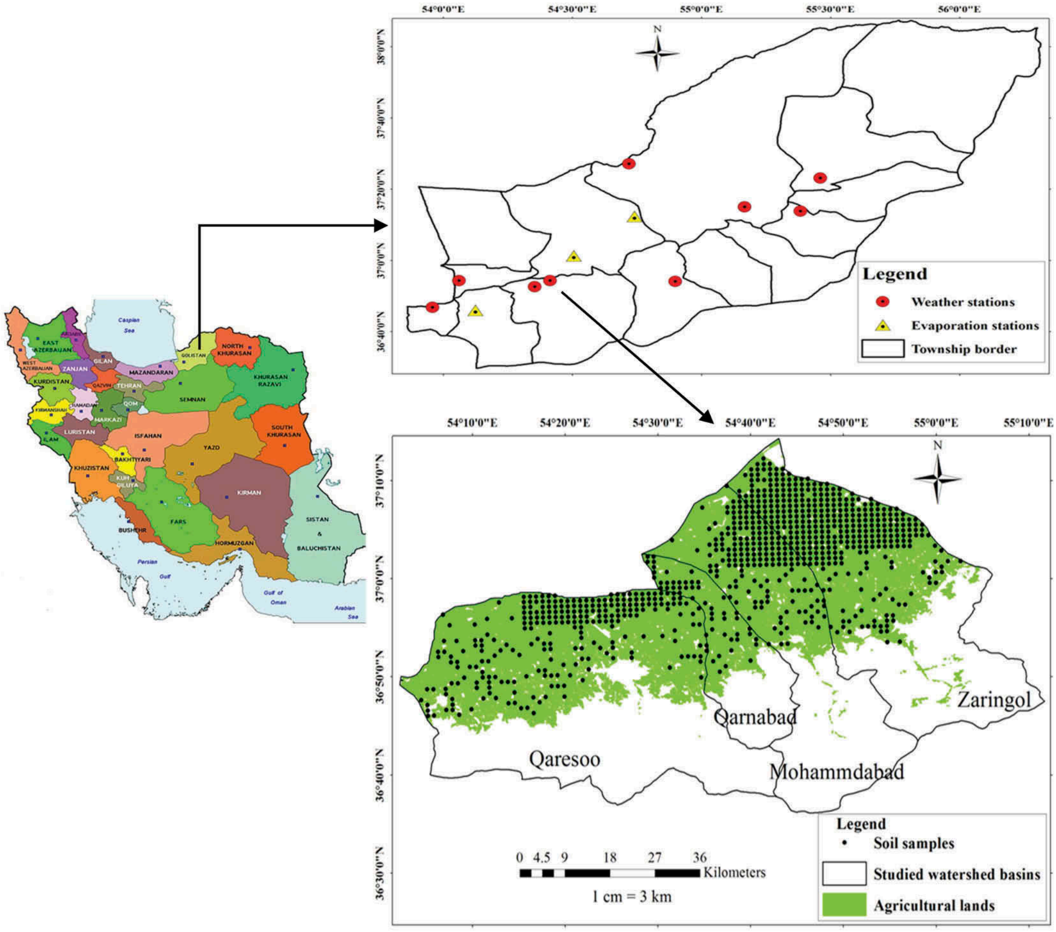

Figure 1. The geographical location of arable lands, soil samples and all used stations in the study basins, Golestan, Iran.

Finally, the provided radiation raster layer was masked using maize fields layer (detected by Landsat8 image, taken on 1 October 2015) via a controlled method by the ERDAS IMAGINE 2014 software (Figure 2). Then, the amount of radiation reaching the maize fields was calculated over the study area.

The CERES-Maize model from the software package DSSAT (Version 4.5) was employed to determine the potential yield of forage maize in the range of the basins studied (Mokhtarpour 2011). The field data of Feyzbakhsh et al. (2015), Mokhtarpour (2011), the Bureau of Meteorology and Regional Water Supply (minimum and maximum temperature and solar radiation), and the Agricultural Research Centre of Golestan province (soil data) were used to run the model aiming at estimating the potential yield. The CERES-Maize model was run for each of the stations. The amount of biomass calculated by the model was subsequently extracted until dough ripening stage. The potential yield layer over the basins was prepared in the GIS environment based on the relationship between the total regional radiation and potential yield. For this purpose, the amount of cumulative radiation received during the growth period of maize in the studied fields was regressed against the corresponding radiation-limited yields of the farms. This relationship was then applied using the Raster Calculator function on the radiation raster obtained from the Area Solar Radiation function to obtain the final layer of potential yield. To determine the potential yield (radiation limited yield) in the form of the raster layer, the potential yield of 12 meteorological

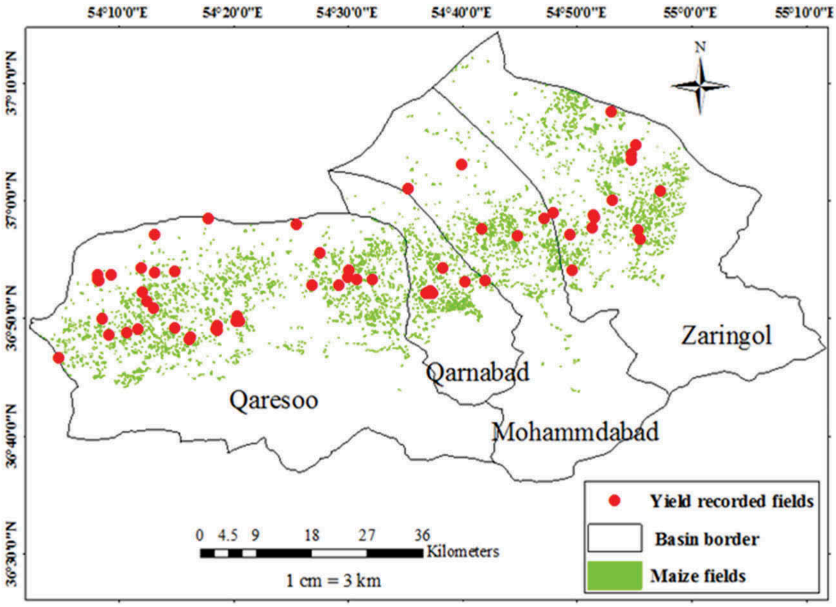

Figure 2. The geographical location of farmlands within the areas under maize cultivation at the basins studied.

stations was first determined through the CERES-Maize simulation model. Afterwards, a regression relationship was established between the simulated potential yield of the 12 stations with the corresponding total sum of radiation for the same stations. After assuring a strong regression relationship between the potential yield and total accumulative radiation (Figure 7a), the relationship was extended to the entire extracted maize grown fields in the GIS environment. It should be noted that due to the low number of meteorological stations in the studied area, the relationship was applied to all four watersheds at once.

The recorded field yields

To record actual yield, 61 maize fields were selected in four basins of Qaresoo, Qarnabad, Mohammadabad, and Zaringol in Golestan province (Figure 2) and their coordinates were determined by GPS (Model Garmin 550). To determine the sample size, Cochran's sample size formula was adopted (Cochran 1963). For this, the margin of error, the population size (field numbers), and the response distribution were considered to be 10% (90% confidence level), 2500 and 50% (which gives the largest sample size), respectively. Farms were chosen to have a favorable geographic distribution throughout the study area. Later, to eliminate the sampling error, depending on the size of the field, a W-shaped path was considered, and five samples of shoot biomass were taken from W five points. For this, a 0.5 × 0.5 m (0.25 m^2) quadrate was used.

The aerial parts were dried in the oven (70°C, 72h), then the actual yield was identified in each field.

Calculation of actual yield using vegetation indices

To generate actual yield layer, regression relationships were used between the indices extracted from the satellite images (LandSat8) and the actual yields recorded on the farms. Multitemporal satellite images of Landsat8 were applied to extract the vegetation indices within four areas of Qaresoo, Qarnabad, Mohammadabad, and Zaringol in Golestan province on 1 October 2015 (www.

usgs.com). The images were examined for geometric and atmospheric corrections followed by spectral, spatial, and radiometric pre-processing procedures (detection of images). Of the ten indices of satellite images, normalized difference vegetation index (NDVI) (Tucker 1979), ratio vegetation index (RVI) (Tucker and Sellers 1986) and soil adjusted vegetation index (SAVI) (Huete 1988) showed significant relationships with recorded actual yields (R^2 was significant in all three cases). Proc reg procedure was used to determine the relationship between extracted indices from satellite images and recorded actual yields. It should be noted that the yield recorded in thirty fields of 61 farms were not used in regression relations. These data were used as independent data for the final test of the raster layer of actual yield. Among the satellite-based indicators, NDVI was selected for further work due to the stronger regression and lower RMSE (Root Mean Square Error, 1.08 t ha^{-1}) compared with the other two indices (i.e. RVI and SAVI). NDVI index is defined as (NIR–R)/(NIR+ R), [where NIR (band 5) and R (band 4) are the reflectance in the near-infrared and red, respectively]. After producing the NDVI-based raster of actual yield, actual yield values in the produced raster (predicted) were compared with the actual recorded values of the 30 observed farms. In addition, the relationship between the actual yields divided by the potential yield multiplied by 100 was used in GIS (Van Wart et al. 2013) to compute ceiling yield (85% of potential yield).

Yield gap

The yield gap was calculated by minus function as the difference between the pixel values of the radiation-limited layer (potential yield) and the yield layer estimated by the vegetation index. The yield gap was then analyzed based on the factors affecting the yield. The process algorithm is presented in Figure 3. The yield gap percentage was obtained through dividing the raster layer of the yield gap by potential raster layer multiplied by 100.

Yield gap fraction

The yield gap fraction was obtained as:

$$\mathrm{YGF} = 1 - \frac{Y_a}{Y_p}$$

where Ya and Yp indicate the actual and potential yields, respectively. The value of regional yield factor varies between 0 and 1. This index determines how to achieve the potential yield at any location. Where yield gap is low (near zero), the yield is equal or close to the potential yield.

Mapping factors affecting the yield gap

Topographic layers: The elevation and slope digital maps were extracted using the 50 m digital elevation model (DEM) and was masked in the area of lands under maize cultivation followed by reclassification (Table 1). Slope layer was generated by 'Spatial Analyst Tools' in Arcmap environment. To do this, the slope function was applied to the Digital Elevation Model layer.

Soil layers: Data from 858 soil samples were used to prepare soil related factors layers [organic mater (OC), pH and electrical conductivity (EC)] (Figure 1). For this, different combined interpolation method-semivariogram models were used and outputs were compared. Finally, organic matter, electrical conductivity (EC), pH and soil texture layers were generated by ordinary kriging-spherical model, universal kriging–hole effect model, ordinary kriging-rational quadratic and Thiessen polygons, respectively. All the maps were provided by 50 × 50 m pixel size for detected maize grown fields. The layers produced were cut for maize grown fields using the 'extract by mask' function.

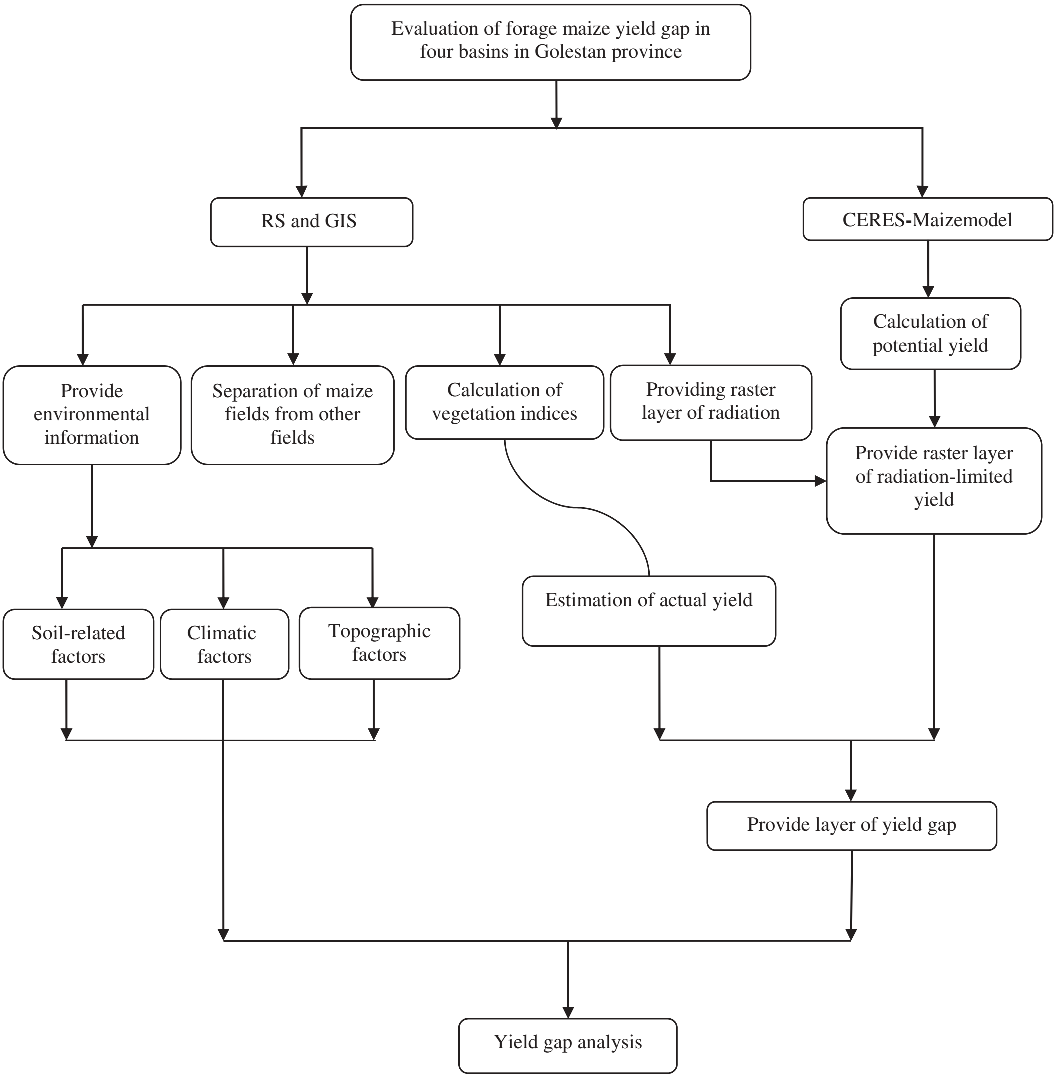

Figure 3. Flowchart for analyzing yield gap of maize.

Layers reclassified based on Zhang et al. (2015). In this regard, S1 represents the land units that are strongly suitable to maize crop production with no restrictions; S2 class is related to those units that are moderately appropriate with some restrictions; S3 belongs to the land units that are marginally favorable with severe restrictions; and S4 represents the land units that are improper for maize growth.

Results and discussion

Potential yield

Estimation of radiation-limited yield by CERES-Maize model

The level of radiation reaching the maize fields at the surfaces studied was determined between 1415.58 and 2196.33 MJm^{-2}(an average of 1841.88 MJm^{-2} during the growing season). The least

Table 1. Ecological requirements for normal maize growth (Tang and Van Ranst 1992; Nour-Mohamadi et al. 1997; Elaalem 2010; Choukan 2012; Khajehpour 2013) .

Environmental factors	Highly Suitable (S1)	Moderately Suitable (S2)	Marginally suitable (S3)	Not suitable (NS)
Precipitation (mm)	> 480	430–480	375–430	< 375
Maximum temperature (°C)	20–25	25–30	30–36	36–42
Minimum temperature (°C)	18–21	15–18	10–15	< 10
Average temperature (°C)	20–23	23–30	30–36	> 36
pH	6–7	5.5–5.6 and 7–7.7	5–5.5 and 7.5–8	< 5.5 and > 8
EC (dS m^{-1})	0–1.7	1.7–2.5	2.5–3.8	> 3.8
OC (%)	> 2	1.5–2	1–1.5	> 1
Slope (%)	> 5	-	-	> 5
Elevation (m)	0–1500	1500–2000	2000–3800	> 3800
Soil texture	Loam and sity loam	Sandy clay loam, silty clay loam and silty	Sandy loam and clay loam	Sandy, clay, sandy loam, sandy clay and silty clay

amount of radiation received was observed in the southern parts of the study area because of the regional topography and the establishment of the fields near highlands and shady areas. The results showed a significant relationship between the amounts of radiation reaching the maize fields of this study and the amount of radiation-limited yield calculated by the CERES-Maize model (Figure 7a). The changes of radiation-limited yield ranged between 19.03 and 22.35 (20.53 per ha on average). One unit increment in the radiation reaching the field surface resulted in an increase of 0.012 t ha^{-1} in the radiation-limited yield. Feyzbakhsh et al. (2015) and Mokhtarpour (2011) estimated the maize potential yields (dry matter) of 16.113 t ha^{-1} (at a density of 6.5 plants per m^2) and 18.49 t ha^{-1} (at a density of 8.5 plants per m^2) using the CERES-Maize model in the city of Gorgan (Golestan province). Other studies have reported relationships between yield and regional radiation (Grassini et al. (2009) for maize; Li et al. (2014) for wheat; Badsar et al. (2017) for wheat). Increasing dry matter production, especially in the linear phase, will increase the production of leaf area. The leaf area index, in turn, will increase the absorption of radiation. This positive feedback is maintained between the absorption of radiation and the increase of dry matter to the end of the linear phase, leading to an increase in dry matter production. For this reason, production will increase as long as the amount of radiation absorbed by the plant community increases (Connor et al. 2011).

Estimation of radiation-limited yield by GIS

The radiation-limited yield was mapped in the maize fields in GIS environment using the regression relationship between the radiation transmitted during the maize-growing season and the radiation-limited yield (dry matter) calculated by the model (Figure 7a). The changes in the potential yield ranged between 15.42 t ha^{-1} and 24.78 t ha^{-1} (Figure 4). An area of 5892.25 ha of the study area (equal to 97.04% of the total surface) produced 20–24.78 t ha^{-1} and only 180 ha showed a yield below 20 t ha^{-1}. The lowest yield (less than 20 t ha^{-1}) was obtained in the southern part of the study area. The potential yield is influenced by radiation, carbon dioxide, and temperature (Evans and Fischer 1999; Van Ittersum et al. 2013). Because there was no temperature limit for the cultivation of maize over the areas studied (unpublished data), the transmitted radiation during the growing season determined the potential yield of the plant. It was reported that the spatial distribution of maize potential yield is affected by solar radiation, temperature, and the effects of these two factors on its phenology (Grassini et al. 2009). In the study of Xu et al. (2017), changes in the potential yield of maize in China were mostly caused by changes in solar radiation rather than by temperature changes.

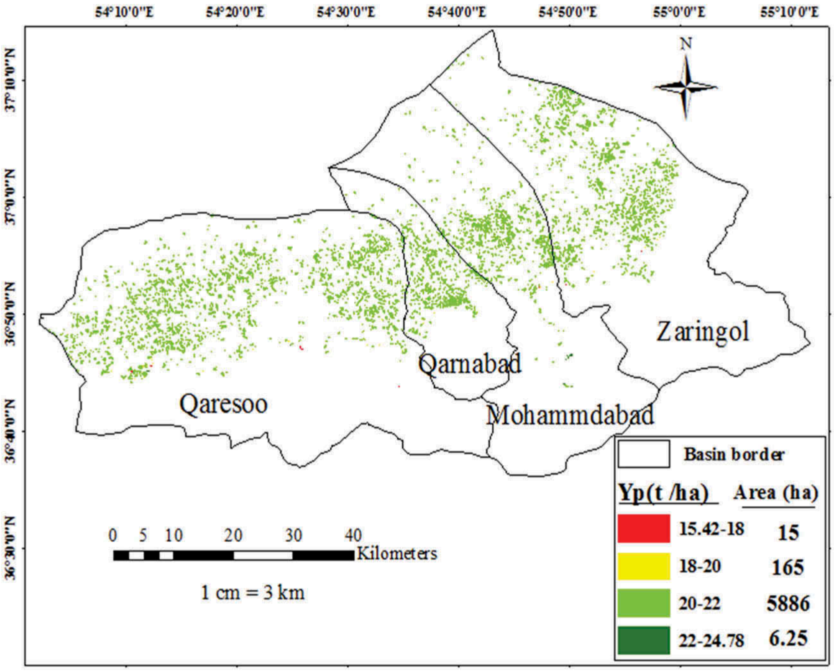

Figure 4. The radiation-limited yield of maize in the arable lands at the basins studied.

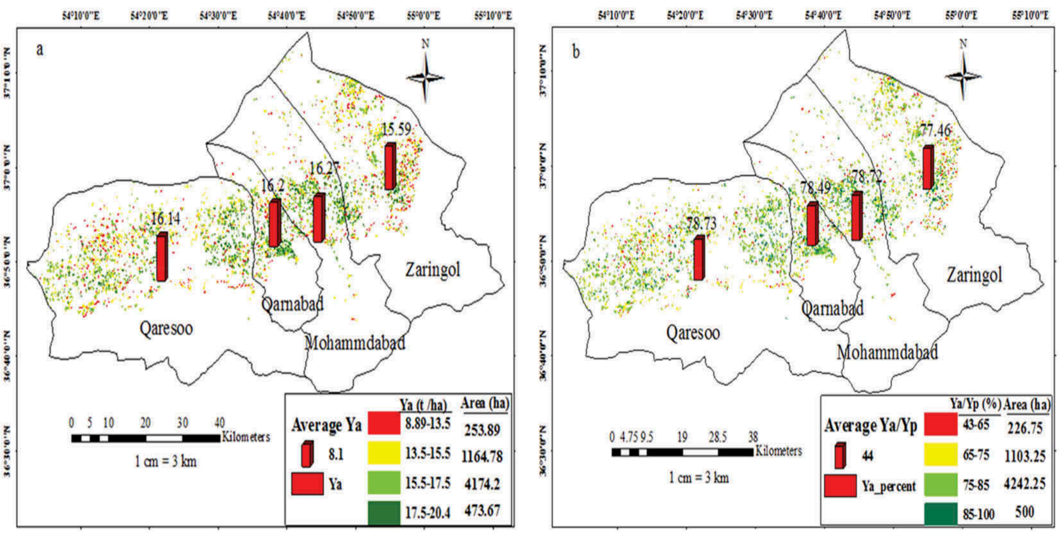

Figure 5. Yield (a) and yield percentage (b) estimated for maize fields within the arable lands of the basins studied.

Estimation of actual yield

There was a linear relationship between the recorded yield and the NDVI index ($p \leq 0.05$). The map of actual yield on the areas studied was provided using a regression equation between the recorded yield and NDVI index (Figure 5a).

The actual yield changes ranged between 8.89 t ha^{-1} to 20.4 t ha^{-1} and the highest area of 4174 ha (equivalent to 68.81% of the total area) belonged to the yield range of 15.5–17.5 t ha^{-1}, of which Qaresoo (45.18%) and Qarnabad (11.64%) basins had the highest and the lowest shares, respectively. The results showed the highest yield in the middle parts of the study area and the lowest yield in the southern, south-eastern, and northern parts. The yield loss in the southern part was caused by topography (slope), and in the north, it resulted from the soil limitations such as lack of organic matter, extra salinity, and inappropriate pH and soil texture.

The map of a comparison between actual and potential yields is presented in Figure 5b. According to the results, 21.9% of the areas cultivated by maize at the four basins studied displayed levels below 75% with 69.86% of the fields showing potential yields of 75–85% whereas only 8.24% of the fields had yields ≥ 85% of potential yield. It has been reported that all farmers are by no means able to achieve the radiation-limited and water-limited potential yields because of poor crop and soil management and the high input costs. Thus, the average regional and national yields can be predicted to reach up to 70–90% of potential radiation-limited or water-limited yields (Cassman et al. 2003; Grassini et al. 2009). Van Wart et al. (2013), by taking into account a maximum yield of 75–85% estimated nationally for the potential yields of rice, wheat, and maize, found that this could have happened in rice and wheat in China and in Germany, respectively. In another study (Pasuquin et al. 2014), attainable maize yield was often 70–80% of the potential yield in irrigated conditions, 55–80%, and 76–110% of water-limited yield in highly favourable and less favourable rained conditions, respectively.

Positive and significant relationships were observed between the predicted yields and those measured in 18 testing points on the yield map obtained using satellite data (Figure 7b). Johnson et al. (2016) properly predicted the yields of spring barley, canola, and wheat using NDVI vegetation index. Zhao et al. (2015) presented evidence that remote sensing can provide a reasonable and reliable estimate of the maize yield. Lobell et al. (2015) found a significant positive relationship between the yields of maize and soybean reported from farmers' fields and the yields extracted from satellite images. Such outcomes were also reported by Mohammadi Ahmad-Mahmoudi et al. (2015) and Badsar et al. (2017).

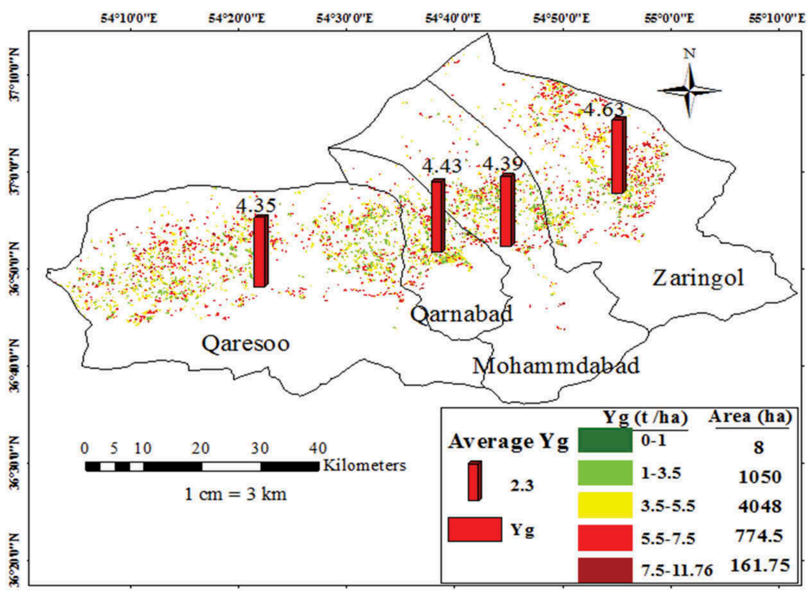

Figure 6. The estimated yield gap in maize fields at the arable lands within the watershed basins studied.

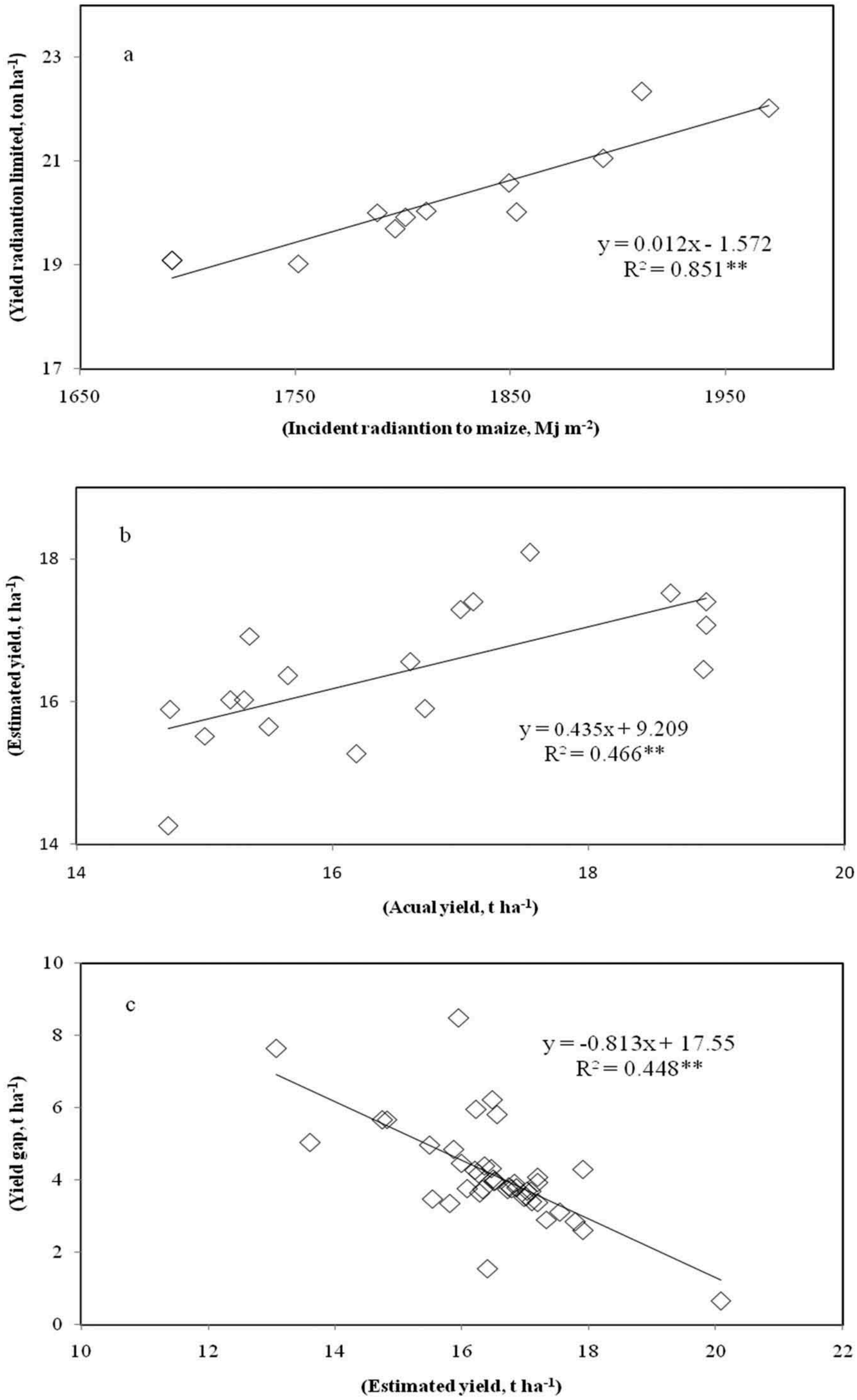

Figure 7. Regression relationship for cumulative incident radiation during maize growing season against radiation-limited yield calculated by CERES-Maize model (a), recorded against predicted yields using NDVI index at 18 testing points (b) and, the estimated yield against yield gap in the corresponding points of recorded yield at the farmers' fields.

Estimation of yield gap

Changes in the yield gap in the maize fields studied are presented in Figure 6. The amount of gap was estimated between 0 and 11.76 t ha^{-1} with an average of 4.44 t ha^{-1} at the study area. The lowest yield gap (0–1 t ha^{-1}) was located in the middle of Zaringol, Mohammadabad, and Qarnabad basins, while the highest levels (7.5–11.76 t ha^{-1}) were obtained in the northwest of Qaresoo basin, northern parts of Mohammadabad basin, and the south-eastern Zaringol basin. In total, the yield gap was lower (less than 3.5 t ha^{-1}) in the middle part of the study area, while higher in the northern and southern Qaresoo, Qarnabad, and Mohammadabad basins as well as in the east and southeast of Zaringol basin (more than 5.5 t ha^{-1}). The variation of the yield gap over the study area was due to management factors such as plant density (ranging from 8 to 12 per m^2), planting date (July 1 to August 6), the type and method of weed control, differences in methods of irrigation and irrigation schedule (unpublished data), soil factors such as a low soil organic matter, high soil salinity, inappropriate pH, soil texture, and topographic factors such as the slope. This is because precipitation (due to irrigated cultivation), temperature, and elevation were suitable during the maize growing season (unpublished data). The results showed that the acidity caused a yield drop in the entire study area and that soil texture, organic matter, slope, and salinity, respectively, caused drops in the yields on 59.12, 97.35, 27.40, and 14.87% of the four basins, respectively (Table 2). Ghaffari et al. (2000) in the Stour basin of Kent City, England, and Kazemi et al. (2015) in Golestan province reported that potential yield occurred 80–100% in the highly suitable class, 60–80% in the suitable class, 40–60% in the poor class, and less than 40% in the not suitable class, in potato and wheat plants, respectively.

Investigating the relationship between potential yield and yield gap showed that there was no significant relationship between these two variables ($R^2 = 0.2055$, $P > 0.05$), while the relationship between actual yield and yield gap was statistically significant ($R^2 = 0.8718$, $P \le 0.05$). Therefore, in the study area, the actual yield is more important than the potential yield in calculating the yield gap (as expected, yield gap was higher on fields with less actual yield, as depicted in Figure 7c) . Such observations were also reported by Lu and Fan (2013) and Badsar et al. (2017) in wheat. Meng et al. (2013) found that the average yield of farmers' maize fields was 48–56% of the potential yield simulated by the model, 51% of the highest yield recorded in the fields, and 64% of the yield recorded in experimental conditions. In another study in Ethiopia (Kassie et al. 2014), the maize yield gap (the difference between average farmers' yield and the yield modelled in water-limited conditions) was reported to be 4.7–6 t ha^{-1}. Farmaha et al. (2016) used a combination of satellite images and models to estimate the actual yield and yield gap of maize and noted a maize yield gap between 30 and 50%. Neumann et al. (2010) accounted a maize yield gap from 0 t ha^{-1} to 9 t ha^{-1} on a global scale. They found that differences in agricultural production were significantly associated with irrigation, accessibility, market influence, agricultural labor, and slope. However, the contribution of each of these factors on the production efficiency is greatly different among various regions of the world. Maize yield was 51% of the potential yield in northeast China and existing reports indicate that this large amount of yield gap can be reduced with the help of effective irrigation, fertilization, herbicides, and plantation density (Liu et al. 2012). Lobell et al. (2002)

Table 2. Area of environmental factors suitability classes for the cultivation of maize at the study area (OC and EC show soil organic matter and electrical conductivity, respectively) .

	Suitability level of environmental factors			
Environmental factors	Highly suitable (ha)	Moderately suitable (ha)	Marginally suitable (ha)	Not suitable (ha)
OC	161.19 (2.66%)	2555.55 (42.15%)	3333.15 (54.98%)	12.96 (0.21%)
EC	5162.13 (85.13%)	186.30 (3.07%)	217.89 (3.59%)	498.15 (8.21%)
pH	–	76.95 (1.27%)	5796.36 (95.58%)	191.16 (3.15%)
Texture	2321.46 (40.88%)	2210.49 (38.92%)	302.13 (5.32%)	844.83 (14.88%)
Slope	4569.21 (72.60%)	1209.33 (19.21%)	128.79 (2.05%)	386.37 (6.14%)

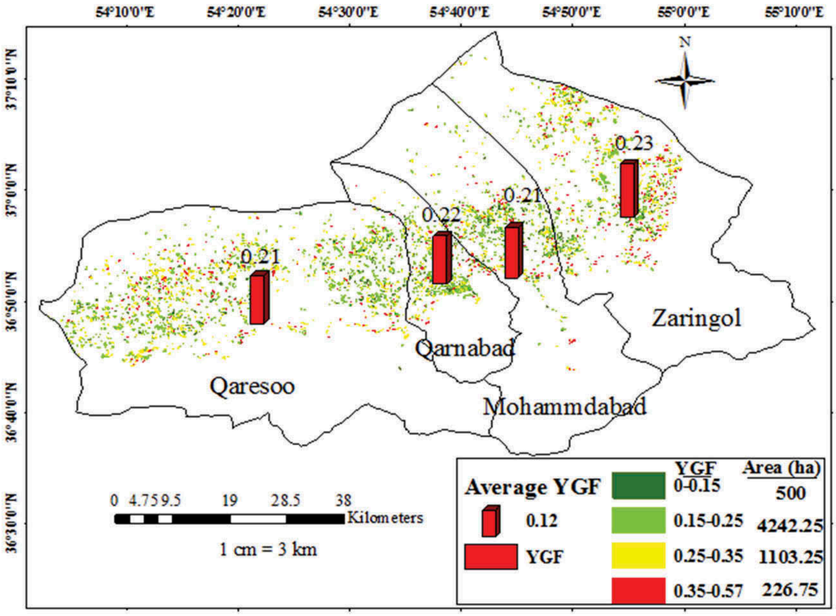

Figure 8. yield gap fractions of maize fields within the arable lands at the basin studied.

studied the impacts of soil, weather, and management on crop production using remote sensing techniques in Mexico and detected that a slight fraction of the yield variation was related to the type of soil (6.6%) and weather (6.4%) while 6.88% of the yield variation was associated with management changes.

Yield gap fraction

Yield gap fraction represents the agricultural management operations in any region. The maps of YGF are shown in Figure 8. The amounts of yield gap fraction changed from 0 to 0.57.

The gap fraction was between 0.15 to 0.25, in a large portion of the study area covering approximately 4242 ha (equal to 69.86%) of the maize fields. The weakest yield gap fraction belonged to the northern Qaresoo and Mohammadabad basins and southeastern Zaringol basin. This index was strongest at the eastern Qaresoo basin, central part of Mohammadabad and Qarnabad basins, and southwestern part of Zaringol basin. Ultimately, YGF values revealed a greater effect of poor management on the yield and yield gap in Zaringol basin compared to the other basins. The yield gap fraction index disclosed that an earlier yield can be achieved by proper management of factors affecting the production at Mohammadabad and Qaresoo basins. Licker et al. (2010) found that yield gap fractions in plants such as maize, rice, soybean, and wheat were between 0 and 1 on a global scale. They divided the index into four classes of 0–0.25, 0.25–0.50, 0.50–0.75, and 0.75–1, which were different depending on the country, weather conditions, and crop management. A maize yield gap fraction of less than 20 to 94.2% was noted by Tao et al. (2015).

Conclusion

The study of the yield gap for a certain crop in an area can show the difference between the actual production of fields and the expected potential. The potential production is obtained when the role of the factors limiting and reducing production reaches zero and all conditions are met to ensure optimum performance.

Radiation and the genetic potential of plants (in particular, the variety) are the most important driving factors of production at a potential level; accordingly, differences in radiation-limited production and actual production by farmers can be a basis for the measurement of yield gap. The amount of radiation absorbed during the growing season is generally not high in Golestan province because of relatively low sunny hours and, consequently, the potential of forage maize production in the province is low compared with many other areas in Iran. Due to the low inherent potential in these areas, the farmers are very far from the expected potential production.

The results showed that the difference between minimum actual yields of farmers and the minimum potential yield observed in the areas is around 6.53 t ha^{-1}. Moreover, the difference between maximum potential yield and maximum actual yield observed is about 4.38 t ha^{-1}, which is substantial considering the average actual production. On the other hand, providing the yield gap raster using the yield of the farms with the help of remote sensing and GIS in this study could separately determine the amount of the yield gap over all the basins studied, which can be very valuable in terms of methodology.

Overall, the results of this study showed high level of changes in the yield gap, but they indicated the opportunity to increase production without increasing the cultivated acreage in the area studied. The results showed that soil acidity is problematic in all studied regions. Therefore, soil acidity modification is one of the most important priorities. Improvement of soil through the increase of soil organic matter (by adding organic amendments and involving soil conservation methods) and reduction of soil salinity through the management of water and soil resources (such as providing the leaching requirement for the crop, keep the right intervals between irrigations, use appropriate fertilizer types, periodical soil testing, soil drainage and etc.) are also in the next priorities.

The yield gap fractions estimated for the basins studied revealed a greater effect of poor management on the yield and yield gap in Zaringol basin compared to the other basins. The yield gap fraction index disclosed that an earlier yield can be achieved by proper management of factors affecting the production at Mohammadabad and Qaresoo basins. The results can be valuable for agricultural policy makers to concentrate management on areas that allow a greater yield increase considering the high water consumption for the production of this crop. Although yield gap analyses of individual crops have been involved to detect probable opportunities for increasing crop production at local to global scales, this could be achieved by altering individual crops arrangement in cropping patterns (Gulipart et al. 2017). Therefore, in regions where the yield gap is high, it is possible to prevent the maize planting in patterns unless the management options can be modified to minimize the yield gap.

Given that the final layer of the yield gap is the result of the difference between the actual yield values and the potential yield and these layers are obtained through the simulation model and regression relations, there will be some deviations in the final results. One of the benefits of pixel-to-pixel calculations for both potential and actual yields is that these errors will decrease in the final average of the yield gap in each watershed basin.

Disclosure statement

No potential conflict of interest was reported by the authors.

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References

Affholder F, Poeydebat C, Corbeels M, Scopel E, Tittonell P. 2013. The yield gap of major food crops in family agriculture in the tropics: assessment and analysis through field surveys and modeling. Field Crops Res. 143:106–118.

Badsar M, Kamkar B, Soltani A, Abdi O. 2017. Yield gap estimation in wheat-grown fields using GIS and RS approach and SSM model (A case study: qaresso basin, Gorgan, Iran). Cereal Res. 7(2):195–215. Persian.

Cassman KG, Dobermann AD, Walters D, Yang H. 2003. Meeting cereal demand while protecting natural resources and improving environmental quality. An Rev Environ Res. 28:315–358.

Choukan R. 2012. Maize and maize properties. Agricultural Training Press (Karaj): Persian; p. 427.

Cochran WG. 1963. Sampling Techniques. 2nd ed. New York: John Wiley and Sons, Inc.

Connor DJ, Loomis RS, Cassman KG. 2011. Crop ecology: productivity and management in agricultural systems. 2nd. Cambrige University Press, Cambridge, UK. 546.

Davis KF, Rulli MC, Garrassino F, Chiarelli D, Seves A, D'Odorico P. 2017. Water limits to closing yield gaps. Adv Water Resour. 99:67–75.

Elaalem M 2010. The application of land evaluation techniques in Jeffara plain in Libya using fuzzy methods. PhD thesis, University of Leicester; p. 268.

Evans LT, Fischer RA. 1999. Yield potential: its definition, measurement and significance. Crop Sci. 39:1544–1551.

FAO and DWFI. 2015. Yield gap analysis of field crops- Methods and case studies, by Sadras VO, Cassman KGG, Grassini P, Aj H, Bastiaansse WGM, Ag L, Milne AE, Sileshi G, Steduto P.eds. FAO Water Reports No. 41, Rome (Italy).

Farmaha BS, Lobell DB, Boone KE, Cassman KG, Yanga HS, Grassini P. 2016. Contribution of persistent factors to yield gaps in high-yield irrigated maize. Field Crops Res. 186:124–132.

Feyzbakhsh MT, Kamkar B, Mokhtarpour H, Asadi ME. 2015. Calibration and Evaluation of the CERES-Maize model in Gorgan climatic conditions. Electronic J Crop Prod. 8(4):25–49. Persian.

Folberth C, Yang H, Gaiser T, Abbaspour K, Schulin R. 2013. Modeling maize yield responses to improvement in nutrient, water and cultivar inputs in sub-Saharan Africa. Agric Syst. 119:22–34.

Ghaffari A, Cook HF, Lee HC. 2000. Integrating climate, soil and crop information: a land suitability study using GIS. proceeding of 4th international conference on integration GIS and environmental modeling (GIS/EM4). Banff (Alberta, Canada).

Grassini P, Thorburn J, Burr C, Cassman KG. 2011. High-yield irrigated maize in the Western U.S. Corn Belt: I. On-farm yield, yield potential, and impact of agronomic practices. Field Crops Res. 120:142–150.

Grassini P, Yang H, Cassman KG. 2009. Limits to maize productivity in the Western Corn- Belt: A simulation analysis for fully irrigated and rainfed conditions. Agric For Meteorol. 149:1254–1265.

Gulipart N, Grassini P, Sadras Victor O, Timsina J, Cassman Kenneth G. 2017. Estimating yield gaps at the cropping system level. Field Crops Res. 206:21–32.

Hajjarpour A, Soltani A, Torabi B. 2015. Using boundary line analysis in yield gap studies: case study of wheat in Gorgan. Electronic J Crop Prod. 8(4):183–201. Persian.

Huete AR. 1988. A soil-adjusted vegetation index (SAVI). Remote Sens Environ. 25:295–309.

Information and Communication Technology Center. 2016. Agricultural statistics, crop year 2014–2015, volume 1: crops. Assistance of planning and Economic. Iran: Ministry of Agriculture- Jihad. p. 174. Persian.

Johnson MD, Hsieh WW, Cannon AJ, Davidson A, Bédard F. 2016. Crop yield forecasting on the Canadian Prairies by remotely sensed vegetation indices and machine learning methods. Agric For Meteorol. 218–219:74–84.

Kassie BT, Van Ittersum MK, Hengsdijk H, Asseng S, Wolf J, Rotter RP. 2014. Climate-induced yield variability and yield gaps of maize (*Zea mays* L.) in the central rift valley of Ethiopia. Field Crops Res. 160:41–53.

Kazemi H, Tahmasebi Sarvestani Z, Kamkar B, Shataei S, Sadeghi S. 2015. Ecological zoning for wheat production at province scale using geographical information system. Adv Plants Agric Res. 2(1):0035.

Khajehpour MR. 2013. Cereal crops. Isfahan (Iran): Jihad Daneshgahi of Isfahan Industrial university Press. p. 763. Persian.

Li P, Yang X, Liu Z, Zhang T, Lu S, Liu Y. 2014. Low yield gap of winter wheat in the North China Plain. Eur J Agron. 59:1–12.

Licker R, Johnston M, Foley JA, Barford C, Kucharik CJ, Monfreda C, Ramankutty N. 2010. Mind the gap: how do climate and agricultural management explain the yield gap of croplands around the world? Glob Ecol Biogeogr. 19:769–782.

Liu Z, Yang X, Hubbard KG, Lin X. 2012. Maize potential yields and yield gaps in the changing climate of northeast China. Glob Chang Biol. 18:3441–3454.

Lobell DB, Cassman KG, Field CB. 2009. Crop yield gaps: their importance, magnitudes, and causes. Annu Rev Environ Resour. 34:1–26.

Lobell DB, Ortiz-Monasterio JI, Addams CL, Asner GP. 2002. Soil, climate, and management impacts on regional wheat productivity in Mexico from remote sensing. Agric For Meteorol. 114:31–43.

Lobell DB, Thau D, Seifert C, Engle E, Little B. 2015. A scalable satellite-based crop yield mapper. Remote Sens Environ. 164:324–333.

Lu C, Fan L. 2013. Winter wheat yield potentials and yield gaps in the North China Plain. Field Crops Res. 143:98–105.

Lv S, Yang X, Lin X, Liu Z, Zhao J, Li K, Mu C, Chen X, Chen F, Mi G. 2015. Yield gap simulations using ten maize cultivars commonly planted in Northeast China during the past five decades. Agric For Meteorol. 205:1–10.
Meng Q, Hou P, Wu L, Chen X, Cui Z, Zhang F. 2013. Understanding production potentials and yield gaps in intensive maize production in China. Field Crops Res. 143:91–97.
Mohammadi Ahmad-Mahmoudi E, Kamkar B, Abdi O. 2015. Comparison of geostatistical and remote sensing data-based methods in wheat yield predication in some of growing stages (A case study: nemooneh field, Golestan province). Electronic J Crop Prod. 8(2):51–76. Persian.
Mokhtarpour H 2011. Impact of planting date and plant density on growth of maize in northern Iran.PhD Tesis, University Putra, Malaysia; p. 260.
Mueller ND, Gerber JS, Johnston M, Ray DK, Ramankutty N, Foley JA. 2012. Closing yield gaps through nutrient and water management. Nature. 490:254–257.
Neumann K, Verburg PH, Stehfest E, Müller C. 2010. The yield gap of global grain production: A spatial analysis. Agric Syst. 103:316–326.
Nour-Mohamadi G, Siadat A, Kashani A. 1997. Agronomy (Vol. 1) cereal crops. Ahwaz: Shahid Chamran University Press. p. 446. Persian.
Pasuquin JM, Pampolino MF, Witt C, Dobermann A, Oberthur T, Fisher MJ, Inubushid K. 2014. Closing yield gaps in maize production in Southeast Asia through site-specific nutrient management. Field Crops Res. 156:219–230.
Ray DK, Ramankutty N, Mueller ND, West PC, Foley JA. 2012. Recent patterns of crop yield growth and stagnation. Nat Commun. 3: 1293.
Sanjani S, Koocheki A, Nassiri Mahallati M. 2012. Quantifying yield potential and yield gap for corn (*Zea mays* L.) in the Northeast Iran. Intl J Agri Crop Sci. 4(22):1692–1700.
Schulthess U, Timsina J, Herrera JM, McDonald A. 2013. Mapping field-scale yield gaps for maize: an example from Bangladesh. Field Crops Res. 143:151–156.
Sileshi G, Akinnifesi FK, Debusho LK, Beedy T, Ajayi OC, Mongomba S. 2010. Variation in maize yield gaps with plant nutrient inputs, soil type and climate across sub-Saharan Africa. Field Crops Res. 116:1–13.
Srivastava AK, Mboh CM, Gaiser T, Ewert F. 2017. Impact of climatic variables on the spatial and temporal variability of crop yield and biomass gap in Sub-Saharan Africa- a case study in Central Ghana. Field Crops Res. 203:33–46.
Tang HJ, Van Ranst E. 1992. Testing of fuzzy set theory in land suitability assessment for rainfed grain maize production. Pedologie. 42:129–147.
Tao F, Zhang S, Zhang Z, Rötter RP. 2015. Temporal and spatial changes of maize yield potentials and yield gaps in the past three decades in China. Agric Ecosyst Environ. 208:12–20.
Tucker CJ. 1979. Red and photographic infrared linear combinations for monitoring vegetation. Remote Sens Environ. 8:127–150.
Tucker CJ, Sellers PJ. 1986. Satellite remote sensing of primary production. Int J Remote Sens. 7(11):1395–1416.
Van Ittersum MK, Cassman KG, Grassini P, Wolf J, Tittonell P, Hochmand Z. 2013. Yield gap analysis with local to global relevance- A review. Field Crops Res. 143:4–17.
Van Wart J, Kersebaum KC, Peng S, Milner M, Cassman KG. 2013. Estimating crop yield potential at regional to national scales. Field Crops Res. 143:34–43.
Wu W, Yu Q, Wang E, Hengsdijk H. 2008. Impact of spatial-temporal variations of climatic variables on summer maize yield in North China Plain. Int J Plant Prod. 2(1):1735–8043.
Xu X, Wang L, Sun D, Liu L, Banson KE. 2017. The impact of climate change on yield potential of maize across China. Int J Plant Prod. 11(1):1735–8043.
Zhang J, Su Y, Wu J, Liang H. 2015. GIS based land suitability assessment for tobacco production and fuzzy set in Shandong province of China. Comput Electron Agric. 114:202–211.
Zhao Y, Chen X, Cui Z, Lobell DB. 2015. Using satellite remote sensing to understand maize yield gaps in the North China Plain. Field Crops Res. 183:31–42.
Zhao Y, Chen XP, Lobell DB. 2016. An approach to understanding persistent yield variation- A case studyin North China. Eur J Agron. 77:10–19.
Zhao Y, Lobell DB. 2017. Assessing the heterogeneity and persistence of farmers' maize yield performance across the North China. Field Crops Res. 205:55–66.