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Crop harvested area, not yield, drives variability in crop production in Iran

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Abstract

Increasing population and a severe water crisis are imposing growing pressure on Iranian cropping systems to increase crop production to meet the rising demand for food. Little is known about the separate contribution of trends and variability of the harvested area and yield to crop production in severely drought-prone areas such as Iran. In this study we (a) quantify the importance of harvested area and yield on trends and variability of crop production for the 12 most important annual crops under rainfed and irrigated conditions and (b) test how well the variability in annual crop areas can be explained by drought dynamics. We use remote sensing based land cover and evapotranspiration products derived from the Moderate Resolution Imaging Spectroradiometer to quantify the extent of cropland and drought severity as well as survey-based, crop-specific reports for the period 2001–2016 in Iran. The intensity of drought stress was estimated using the annual ratio between actual and potential evapotranspiration. We found that trends in the production of specific crops are predominantly explained by trends in harvested crop area. Besides, the variability in the harvested area contributed significantly more to the variability in crop production than the variability in crop yields, particularly under rainfed conditions (seven out of nine crops). In contrast, variability in the production of heavily subsidized crops such as wheat was predominantly explained by yield variability. Variability in the annual cropland area was largely explained by drought, in particular for the more arid regions in the south of the country. This highlights the importance of better and proactive drought management to stabilize crop areas and yields for sufficient food production in Iran.

1. Introduction

Iran is the second largest country in the Middle East, covering an area of 1.65 million km^2 with 0.13 million km^2 under crop cultivation (Iran's Agricultural Ministry 2019). Wheat (56% of the total growing area), barley (18%) and rice (3%) are the main annual crops growing in Iran (Iran's Agricultural Ministry 2019). Iran has a very diverse temperature pattern, ranging from 5 °C annual mean temperature in the northwest to 27 °C in southern parts of the country (figure 1). The annual precipitation sum varies between 62 mm year^{-1} in central deserts and 600 mm year^{-1} in the north and northwest. Precipitation also shows higher temporal dynamics than temperature (figure 1).

The population of Iran has increased from 20 to 80 million over the last 50 years (Poorolajal 2017). Furthermore, the new population policy of Iran aims for a population of 150 million by 2050 (Khamenei 2014). The quantity of agricultural production including crop production needs to be significantly enlarged to meet the growing demand for food and avoid food insecurity in Iran (Karandish and Hoekstra 2017). Climate change and water crises in Iran make this task remarkably more challenging

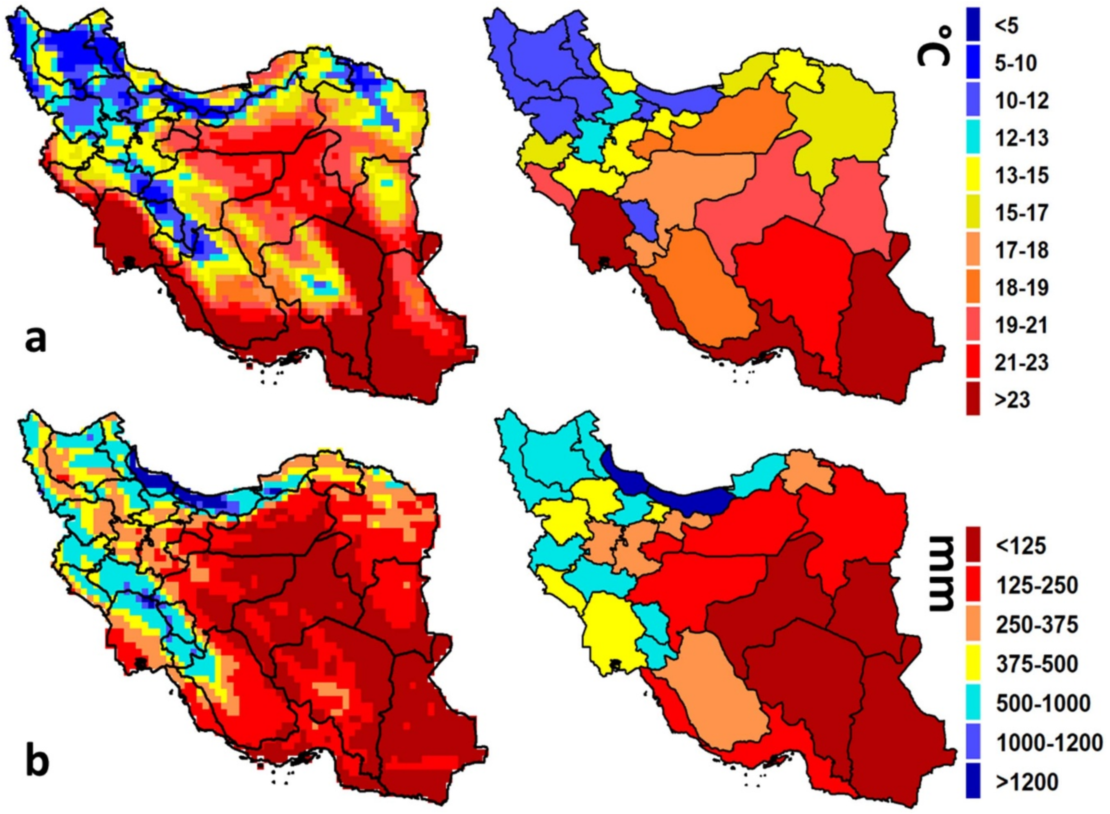

Figure 1. Spatial pattern of mean temperature (a) and annual precipitation sum (b) in the period 2001–2016 across grid-based (left) and province scales (right) in Iran.

(Madani 2014, Murtagh and Legendre 2014, Rezaei and Lashkari 2019). Based on FAO statistics, crop production in Iran increased by 0.93 million tonnes per year from 2000 to 2018 (FAO 2019), with the extension of irrigated lands boosting crop production (Mesgaran *et al* 2017). However, the reported increase in crop production did not meet the country's growing demand for agricultural products so that deficits in net annual agricultural trade increased from −2 to −4 billion US dollars from the 1990s to 2010s (FAO 2019). Climate change projections suggest a 2.5 °C increase in temperature and a 35% decline in precipitation in Iran over the next few decades (Mansouri Daneshvar *et al* 2019). The negative impacts of climate change on major crops such as maize would decline the yield by as much as 22% under these warming scenarios compared with baseline conditions (Rezaei and Lashkari 2019).

Improvement of crop production by introducing new technologies and investment in agricultural infrastructure (Fischer 2015), increasing food imports (Farajzadeh and Esmaeili 2017) and expanding cropland areas are possible options for tackling the growing demand for food in Iran. The investments in the agricultural sector and/or food imports have been heavily suppressed by international sanctions on Iran's economy (Madani 2014, Farzanegan *et al* 2015). Therefore, expanding the cropping area (mostly irrigated lands) seems to be the most accessible option for increasing crop production in Iran. On the other hand, only 2.6% (4.2 million ha^{-1}) of the land of Iran is classified as suitable for agriculture (Mesgaran *et al* 2017).

Irrigated land covers about 8 million ha, more than 50% of the total cropland area of Iran (Iran's Agricultural Ministry 2019). Drought stress and the availability of water for irrigation are the most critical limiting factors for the expansion of cropping areas in Iran (Faramarzi *et al* 2010). Also, the potential for crop production in most of the land in the centre, east and southeast of Iran is limited by low soil organic carbon and high salinity (Mesgaran *et al* 2017). The intensity of agricultural drought increased significantly in the north, northwest and centre of Iran in the period 1980–2013 (Golian *et al* 2015). Besides, climate change projections indicate that the difference in annual precipitation sum between dry and wet regions of Iran will further increase (Abbaspour *et al* 2009).

All of these challenges increase the pressure on the agricultural water resources of Iran (Madani 2014). Therefore, it is fundamental to have a better understanding of the constraints on crop production, which can inform adaptation strategies and consequently improve food security. Previous studies conducted on the effects of drought and water availability on crop production mainly focused on the response of crop yields to water shortages (Iizumi and Ramankutty 2015). However, drought also affects the growing area of crops, particularly in arid and semi-arid regions (Lesk *et al* 2016). Little is known about the separate contribution of changes in harvested area and yield to the variability and trends in crop production in Iran, how these changes can be effectively monitored and how the frequently observed droughts impact crop growing areas. Therefore, the objectives of the study were to (a) quantify the importance of trends and variability of the harvested area and yield for the production of the most important crops in Iran and (b) to assess the relationships between remotely sensed (RS) agricultural drought and cropping extent (not crop-specific) and reported crop-specific yield and area in Iran.

2. Materials and methods

2.1. Disentangling the impact of changes in crop area and crop yield on trends and variability of crop production

Harvested area, yield and production of the 12 most important annual crops, including wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), rice (*Oryza sativa* L.), grain maize (*Zea mays* L.), sugar beet (*Beta vulgaris* L.), cotton (*Gossypium hirsutum* L.), soybean (*Glycine max* L.), potato (*Solanum tuberosum* L.), lentil (*Lens culinars* Medic.), rapeseed (*Brassica napus* L.), beans (*Phaseolus vulgaris* L.) and chickpea (*Cicer arietinum* L.), were extracted from statistical yearbooks (Iran's Agricultural Ministry 2019) for rainfed and irrigated conditions at province level for the period 2001–2016. To avoid inconsistency in the administrative setup, we kept the provinces as of the year 2001 for the whole study period (figure 2). Trends in harvested area, yield and production were calculated for all crops relative to the year 2001 as the starting year of the study. Next, the time series were de-trended for each crop using linear de-trending (Rezaei *et al* 2015). Multiple linear regression was employed to describe the relationship between specific crop production under rainfed and irrigated conditions (as the dependent variable) and harvested area and crop yield (as independent variables) using the 'Rattle' package in R (Williams 2011). The relative importance of independent variables on the dependent variable was tested using the Lindeman, Merenda and Gold (lmg) metric (R^2 partitioned by averaging over orders) implemented in the 'relaimpo' package in R (Grömping 2006). Bootstrap resampling (1000 bootstrap runs) was used to estimate the probability distribution of each variable's contribution to R^2 and to calculate 95% confidence intervals to determine the significance of a difference between the impact of the independent variables (Grömping 2006). The statistical test was conducted on absolute and de-trended data. Comparison of results obtained from absolute and de-trended data shows if trends caused by external factors such as technological change affected the importance of the study variables for crop production (figure 2).

2.2. Assessing the impact of drought on cropland extent

Annual cropland area was derived from the MCD12Q1.006 (Friedl and Sulla-Menashe 2019) land cover product with 500 m resolution. All pixels with a cultivated area of at least 60% were selected and aggregated to cropland extent per 0.5° × 0.5° grid for each time step. The pixels labelled as mosaic cropland/natural vegetation (i.e. shifting small-scale cultivation with other vegetation such as natural trees, shrubs or herbaceous vegetation, in which none of the components covers more than 60% of the landscape) were not included in the analysis due to the small presence of this class in the study area as well as the potential impact of mixed pixels (Zhang and Roy 2017). For the selected cropland pixels, the ratio between the annual sum of actual evapotranspiration (AET) and the annual sum of potential evapotranspiration (PET) was computed as a crop drought stress indicator. This information is available for whole cropland areas but not for specific crops. The long-term mean of the AET/PET ratio is considered as an aridity indicator while the deviation of the annual AET/PET ratios from the long-term mean is used as an indicator for drought or wetness (Meza *et al* 2020). Evapotranspiration time series were extracted from the MOD16A2.006 product (Running *et al* 2015). The original dataset has an 8 day resolution and provides the sum of AET and PET for the 8 days at 500 m pixel resolution. This dataset is derived based on the Penman–Monteith model using meteorological reanalysis data as well as vegetation property products, such as land cover, fraction of photosynthetically active radiation, albedo and leaf area index, and it has acceptable accuracy (Mu *et al* 2011, Wang *et al* 2018). Based on this, monthly and yearly sums were calculated, which was followed by the exclusion of low-quality pixels (e.g. cloud-contaminated cells) based on the quality information of the dataset pixel-level quality control layer (ET_QC_500 m). The scaling factor of 0.1 was applied to both AET and PET data. Finally, annual AET and PET for croplands were aggregated to 0.5° × 0.5° resolution using the median. The datasets were accessed and processed using Google Earth Engine (GEE) due to the availability of the data in the GEE public data catalogue (Gorelick *et al* 2017). The variables extracted from Moderate Resolution Imaging Spectroradiometer data (cropland area and evapotranspiration) do not provide crop-specific information but represent cropland in general, and thus the sum of all specific crops (figure 2). We also tested the relationships between AET/PET ratio and the harvested

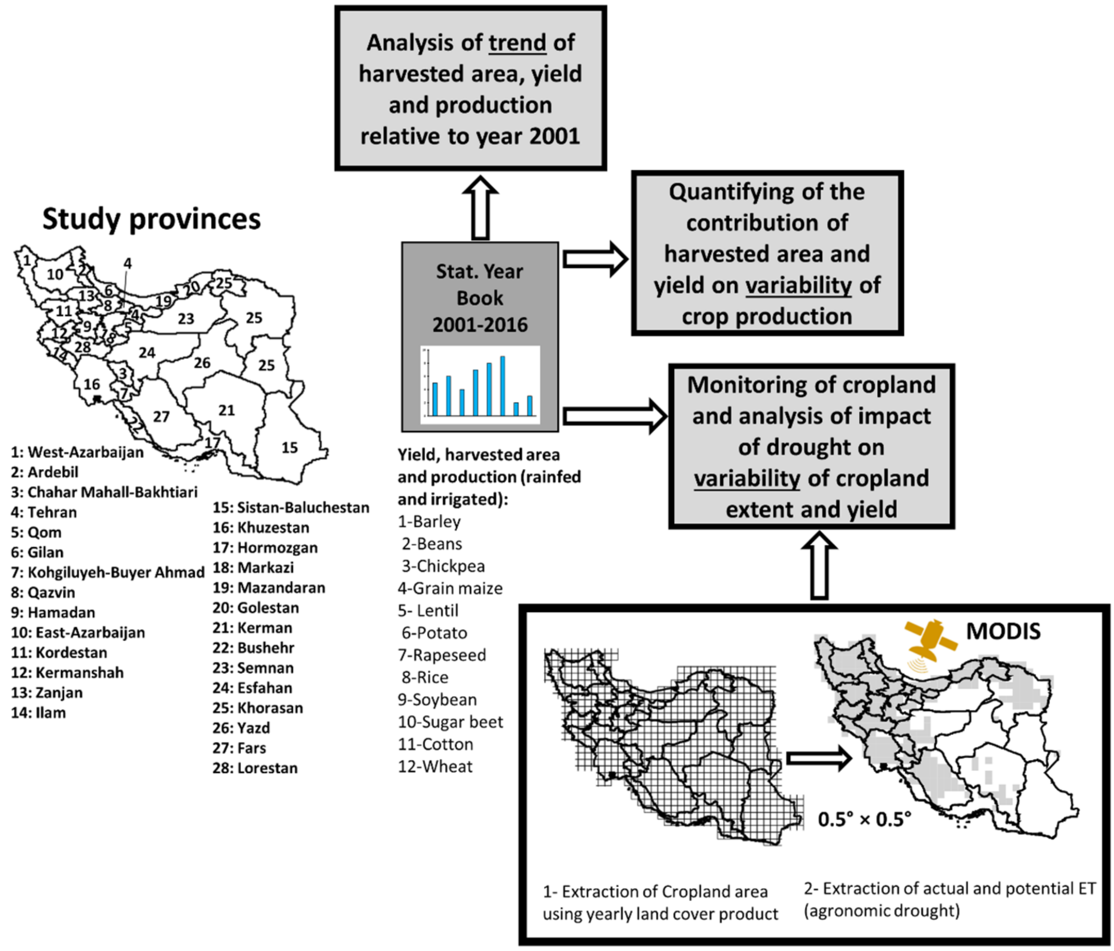

Figure 2. The study region and the workflow to process the remote sensing and ground-based information used to track the cropland/harvested area and relationships between cropland area and agronomic drought stress intensity during the study period in Iran.

area divided for winter (October–July) and summer (April–September) seasons. The analysis provided the information quantifying the difference between season-specific AET/PET ratio and harvested area compared with the annual analysis for rainfed wheat, rainfed barley, grain maize and rice as representative winter and summer crops.

2.3. Assessing the impact of drought on the harvested area and crop yield

We computed the long-term mean AET/PET ratio for each province and the deviation of the annual AET/PET ratios for the period 2001–2016 from the long-term mean ratio as the area-weighted mean across pixels containing at least 60% cropland. Province-level total harvested area was calculated for each year as the sum of the harvested area for all 12 crops. The harvested area anomaly was then calculated as the relative deviation of the annual harvested area from the value estimated using the trend line. Similarly, the crop yield anomaly was computed for each province and year as a relative deviation from the crop yield trend. Total crop yield anomaly was then calculated as harvested area-weighted mean of the crop-specific relative yield anomalies. The Pearson correlation coefficient between the drought indicator and the harvested area anomaly or crop yield anomaly was then derived for each province based on the data for the period 2001–2016 (figure 2). We also tested the relationship between climatic variables and RS estimated cropland areas at country scale. The climate data were mean temperature and precipitation sum obtained from the ERA5 atmospheric re-analysis (0.25° × 0.25°) for the period 2001–2016 (Hersbach *et al* 2020).

3. Results

Results of trend analysis showed a positive trend in yield since the year 2001 for nine out of 12 irrigated crops and seven out of nine rainfed crops (figure 3). In contrast, the trend of the harvested area was negative for eight irrigated and rainfed crops (figure 3). The sign of the trend (positive/negative) was similar between production and harvested area for eight out of the nine rainfed crops and for seven out of 12 irrigated crops. On the other hand, the sign of the trend was similar between production and yield for only

Figure 3. Trends in annual time series of crop production, harvested area and yield of the 12 most important crops under irrigated and rainfed conditions for the period 2001–2016. The values indicate the change in percentage per year, with the year 2001 assumed as a reference year.

three of the nine rainfed crops and six of the 12 irrigated crops (figure 3).

Analysis of the importance of harvested area and yield on the variability of crop production showed a reasonably similar pattern (except for wheat and barley) for rainfed and irrigated conditions in the period 2001–2016 (figure 4(a)). We found that harvested area had a more substantial impact on the variability of rainfed crop production than crop yield for all crops except wheat and barley (figure 4(a)). In particular, it showed a statistically significant contribution (percentage of response variance between 0.6 and 0.9) in explaining the variance of production for potato, maize, cotton, rapeseed and soybean under rainfed conditions (figure 4(a)). The importance of yield and harvesting area on the variability of irrigated crop production was more diverse (figure 4(a)). The contribution of yield was significant in explaining the variability of production of wheat, barley, beans and potato under irrigated conditions, while the harvested area showed significant capability (0.50–0.77) in explaining the variance of crop production for chickpea, lentil, grain maize, sugar beet, rapeseed and soybean (figure 4(a)).

Analysis of the importance of yield and harvested area on the variability of total production was also performed using de-trended data (figure 4(b)). The results showed a similar pattern between absolute and de-trended data under rainfed conditions, which means that change in the harvested area also mainly determined the inter-annual variability in crop production (figures 4(a) and (b)). In contrast, de-trending changed the importance of yield and harvested area for irrigated chickpea and potato compared with absolute data (figures 4(a) and (b)). The significant importance of harvested area on the

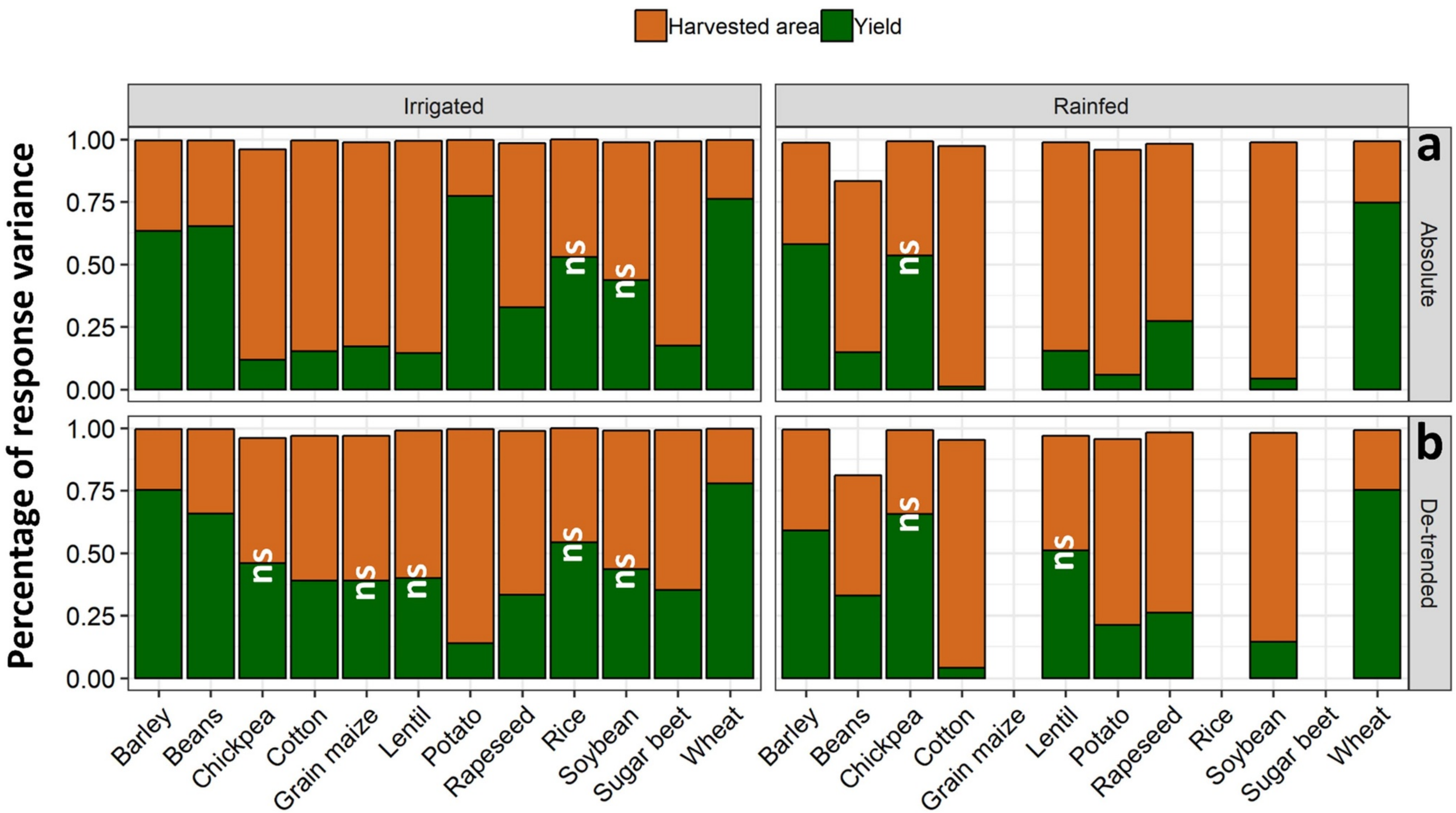

Figure 4. The relative contribution of variability in harvested area and yield to variability in crop production of the 12 most important crops under irrigated and rainfed conditions using absolute (a) and de-trended (b) data in the period 2001–2016 in Iran. High values mean a higher impact on crop production. Significance means either harvested area or yield has significantly more impact on crop production than the other variable. ns , non-significant.

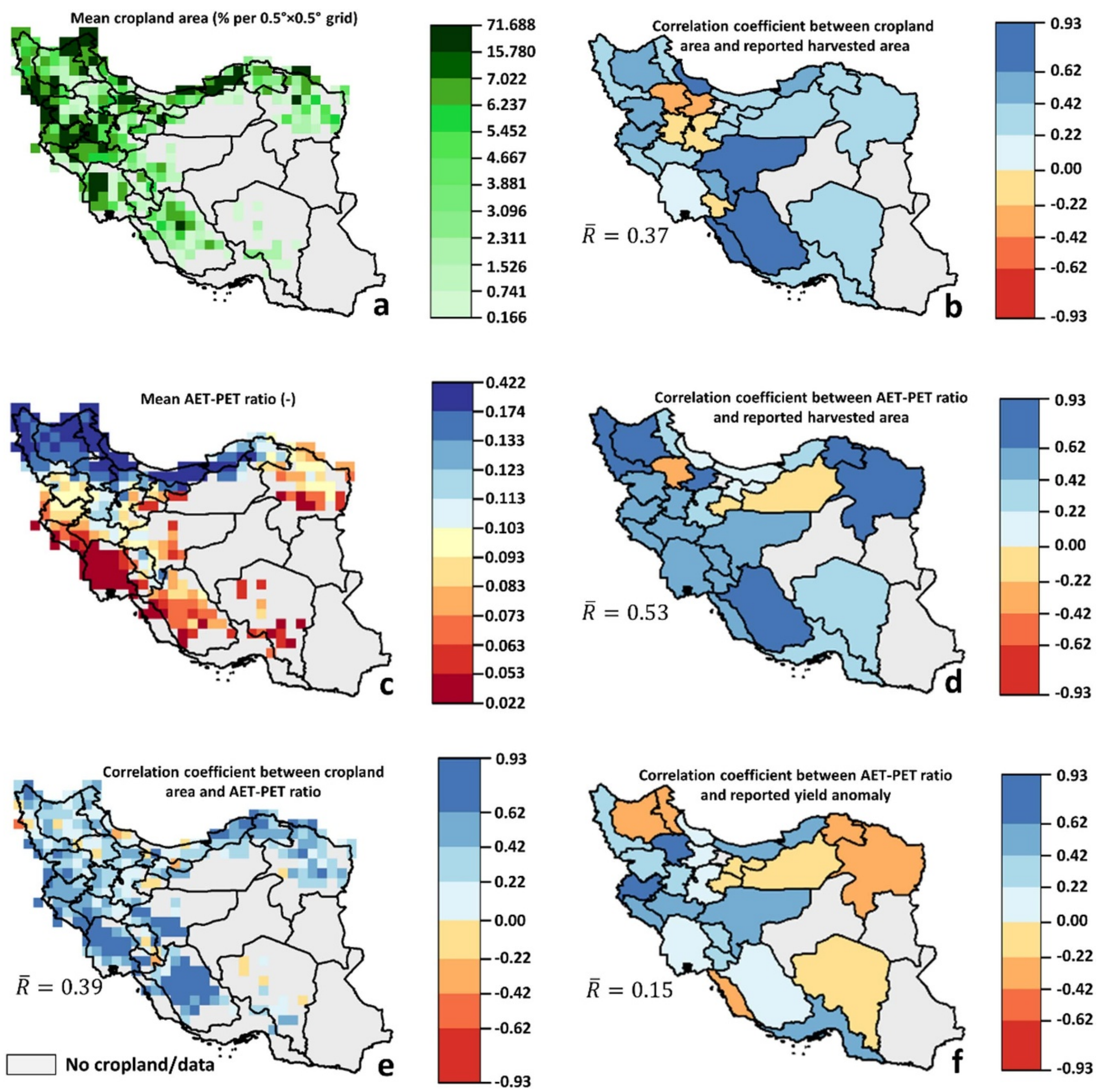

Figure 5. Mean cropland extent for the period 2001–2016 as a fraction of the total grid area (a) and Pearson correlation coefficient between estimated cropland extent and reported harvested area at the province level (b). Mean ratio between annual AET and annual PET in the period 2001–2016 (c) and Pearson correlation coefficient between reported harvested area and AET/PET ratio as agricultural drought indicator (d). Pearson correlation coefficient between the extent of estimated cropland area and agricultural drought estimated based on RS information (e) during the study period (2001–2016). Pearson correlation coefficient between agricultural drought and reported yield anomaly in the period 2001–2016 (f). High AET/PET ratios indicate humid conditions while low AET/PET ratios show arid conditions.

production of chickpea was counterbalanced by yield after de-trending. Chickpea showed a strong trend in the harvested area during the study period (figure 3) which was removed by de-trending. Results for potato differed, as the significant impact of yield effect on production due to an increased yield trend (figure 3) transformed to significance of the importance of harvested area by de-trending (figure 4(b)).

The mean cropland extent in the period 2001–2016 was between 1% and 72% in the $0.5^\circ \times 0.5^\circ$ grid across Iran (figure 5(a)). The largest cropland areas were located in the north and northwest (figure 5(a)). The variability of RS-driven cropland area estimation indicated a positive correlation (0.22–0.93) with a variability of reported harvested area in 22 out of 26 study provinces (figure 5(b)). Five provinces mainly located in the transitional climate zone (from cold–wet to warm–dry) with remarkably high spatiotemporal climatic variability (supplementary figure 1, available online at stacks.iop.org/ERL/16/064058/mmedia) showed a negative correlation between survey-based harvested area and RS cropland extent (figure 5(b)). Due to a high risk of late spring frost damage and instability of in-season precipitation, the risk of crop failure is relatively high for these provinces. RS data captured both the harvested and unharvested cropland (with no consideration as to whether it was harvested or not), which could result in mismatches between reported and RS data in those provinces. Based on RS observations, the cropping systems in the north and northwest of Iran experienced the lowest drought level while other parts of the country were exposed to a fairly higher level of drought during the study period (figure 5(c)). The variability of RS agricultural drought (AET/PET ratio) showed a strong correlation ($\bar{R} = 0.53$) with the variability of reported harvested area (figure 5(d)). The variability of the AET/-PET ratio showed a correlation with the variability of cropland areas ($\bar{R} = 0.39$) for most of the cropland grids at country scale (figure 5(e)). The highest correlation (0.42–0.93) was in southern areas where irrigated cropping prevails (figure 5(e)).

The relationships between drought and reported yield anomaly were weaker ($\bar{R} = 0.15$) than the correlation with reported harvest area (figure 5(f)). There was a remarkable difference in variability among cropland area and climatic factors including mean temperature and precipitation sum. The correlation between variability of cropland area and mean temperature was weak ($\bar{R} = 0.09$) at the country scale (supplementary figure 2). The most negative correlations (−0.62 to −0.93) were obtained for the southern part of the country (supplementary figure 2). In contrast, the variability of precipitation sum showed a reasonable correlation (0.20) with the variability of the cropland area at the country scale (supplementary figure 2).

4. Discussion

The results of the current study showed a remarkable impact of the harvested area on total crop production in Iran. Most of the studies investigating the effects of extreme events such as drought on food security at large scales explicitly focused on crop yield (Deryng *et al* 2014, Zhao *et al* 2017, Webber *et al* 2018). It seems that such a focus on the influence of crop yield on crop production may lead to an incomplete overview of the driving factors behind change of crop production in semi-arid regions. A global analysis indicated that the reduction of crop production by drought was influenced not only by the decline in yield but also by a reduction in harvested area, while production decline due to heat was only related to a reduction in yield (Lesk *et al* 2016). The few regional studies conducted to understand the contribution of change in the harvested area on crop production showed a relatively strong contribution of the harvested area to crop production, particularly under extreme climatic conditions (Koide *et al* 2013, Marston and Konar 2017). They suggest that climate extremes such as drought can force farmers to concentrate the limited available water on a smaller area to ensure reliable yield which results in a smaller variability of yield compared with harvested area (Lipper *et al* 2014, Iizumi and Ramankutty 2015).

Unlike other crops, the variability of wheat and barley production was mainly affected by crop yield but not by harvested area (figure 4). Self-sufficiency in cereal production (mainly wheat) is one of the main aims of policymakers in Iran (Amid 2007). A wide range of subsidiary programmes encourages farmers to have continuous wheat cultivation (Amid 2007) to reduce wheat imports, which could be the main reason for the negligible impact of variability of the harvested area on the variability of wheat and barley production in Iran.

This study also used RS data because inconsistencies in survey-based official statistics have often been reported in Iran (Doostmohammadi *et al* 2008). The suitability of RS information for detecting long- and short-term change in cropland areas has been previously assessed over temperate environments (Gumma *et al* 2016). The mean of the AET/PET ratio showed a distinguishable pattern between lower aridity in northern Iran (0.174–0.422) and very high aridity in southern Iran (0.022–0.053) (figure 5(c)). The variability of the AET/PET ratio used as drought index designated a robust correlation (0.42–0.93) with the variability of reported harvested area in 24 out of the 26 study provinces (figure 5(d)). Other studies that used different indicators also demonstrate the spatial variability in drought stress intensity across Iran (Morid *et al* 2006, Raziei *et al* 2009, Shahabfar *et al* 2012). In particular, a significant increase in the standardized soil moisture index (used as an indicator of agricultural drought) was detected in the period 1980–2013 across the north, northwestern and central parts of Iran but not the east of Iran (Golian *et al* 2015).

The observed patterns and strong relationships between variability of cropland area and precipitation/drought stress index compared with mean temperature highlight the importance of water availability to ensure sustainable crop production in Iran (Bannayan *et al* 2010, Faramarzi *et al* 2009, 2010). A limited number of studies, which mainly used RS information, have analysed the relationship between drought intensity and change in cropland area. The significant decline in harvested area of rice in the year 2002 compared with other years was primarily related to severe drought in India (Gumma *et al* 2019). The results of a region-specific study showed that the years with exceptional drought resulted a decline of up to 12% in the harvested area in California (Marston and Konar 2017).

A critical limitation of the current study is that gridded annual data for the distribution of specific crops have not been available so that crop-specific AET/PET ratios could not be calculated. Such information may increase the strength of the relationships between the harvested area and RS drought by constraining the drought indicator to the crop-specific growing seasons. We further tested the effects of considering the growing period of wheat, barley, grain maize and rice as representative winter and summer crops by calculating the drought indicator separately for the growing season of winter and summer crops. However, this did not result in increased correlation coefficients between reported harvested area and drought indicator at country scale compared with the annual analysis (figure 5(d), supplementary figure 3).

5. Conclusions

Based on the main findings of this study we conclude that: (a) the impact of changes in the harvested area on crop production was undermined, particularly for rainfed cropping systems of arid regions such as Iran. (b) The occurrence of drought affects not only crop yield but also cropland extent, which may have an additive impact on crop production across arid regions. (c) Remote sensing information can provide a substantial service in monitoring cropland extent in arid regions with limited ground-based information. Further research is needed to explore whether cropland extent and harvested crop area can be forecast based on the existing drought situation, which would be a fundamental tool for early warning systems.

Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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