Drought and Climate Change in Jordan: An Analysis of the 2008 - 2009 Drought and Climate Change Impact

Steven Gilbert
Pennsylvania State University
Advisor: Justine Blanford

Abstract

As one of the most water scarce countries in the world, climate change represents a significant threat to Jordan's water and food security. Recent severe drought events suggest that climate change may already be increasing the frequency and intensity of drought in the Middle East. From 2007-2009, a severe drought in the Middle East caused widespread water and food insecurity, fueling rural to urban migration and conflict. While considerable research has examined the impact of this drought on Syria, there has been little analysis of how this drought affected Syria's southern neighbor Jordan. In this study, drought severity and intensity was assessed temporally and spatially to determine how the 2007-2009 drought affected agricultural production and population. Historical climate data was used to place this drought in context of past drought events; a composite drought index was used to identify areas most affected; and future temperature and precipitation scenarios were used to examine how Jordan may be affected by climate change. Finally a comparative analysis was conducted between Jordan and Syria. Overall, the findings from this study indicate that the frequency of droughts has increased during the past sixty years. For the 2007-2009 drought, precipitation was lowest during the winter of 2008-2009 and was preceded by four consecutive years of drought. An estimated 4.7 million people were affected and 52 % of Jordan's cropland was negatively impacted by the drought. Although Jordan was impacted by the same drought as Syria, the drought was most severe in Syria during the winter of 2007-2008 rather than 2008-2009 analyzed for Jordan. The drought was much less severe in relative terms in Jordan and had a smaller impact on agriculture due to Jordan's historic decrease in production of these crops and increased reliance on imports.

Introduction:

Jordan is a small arid country located between Israel, Saudi Arabia, Syria, and Iraq (Figure 1). Although it has just 9.8 million people (Jordan Department of Statistics, 2017) and lacks the natural resource wealth of regional neighbors, it is a key U.S. ally and pivotal player in the region (Sharp, 2017). Its strategic location and relative stability serve as a buffer between many of the conflicts that plague the region. Although Jordan remains relatively stable, climate change threatens to exacerbate water and food insecurity and could destabilize the country.

As one of the driest countries in the world, Jordan faces severe water scarcity. Water resources per capita are among the lowest in the world and the situation is getting worse (World Bank, 2016). Water demand has increased due to population growth, economic development, and an influx of refugees from neighboring countries. To meet the growing needs of its population Jordan is extracting groundwater resources at an unsustainable pace, threatening water resources for future generations. Decreased precipitation and extreme drought due to climate change could exacerbate these existing problems.

Figure 1: Map of Jordan

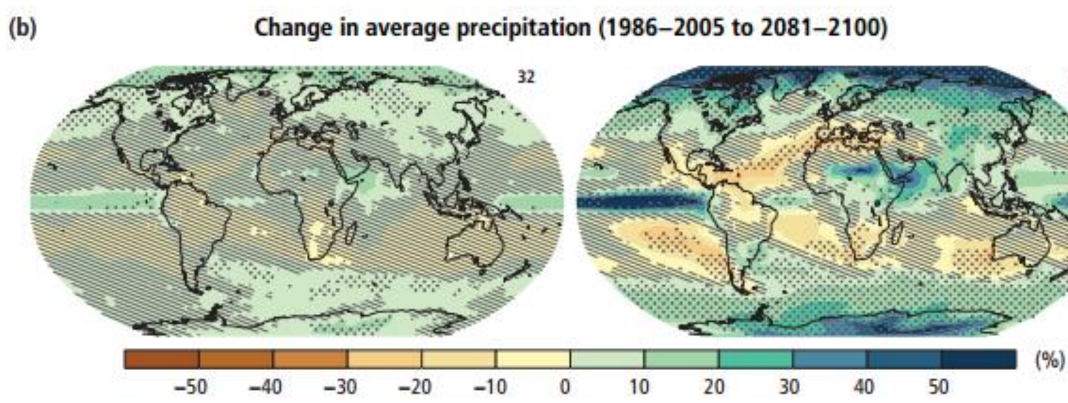
Climate Change Introduction

Although the earth's climate changes naturally over time, climate change is primarily used to refer to the recent and continuing rise in global temperatures. Since 1880, temperatures globally have risen 0.85 degrees Celsius (IPCC, 2014a). Scientists have attributed most of the warming since 1950 to the release of greenhouse gases which trap heat near the earth's surface (Gillis, 2015). Climatologists project that global temperatures will rise another 0.3 and 4.8 degrees Celsius in the next century depending on the world's ability to reduce emissions (IPCC, 2014b). Climate change models for the Levant region, which encompasses Syria, Lebanon, Israel, Jordan, and the Palestinian territories predict and increase of between 2.5°C and 3.7°C in the summer and 2.0°C to 3.1° C in the winter by 2050 (Brown & Crawford, 2009).

Effect of Climate Change on Water Resources

Increases in temperature and changes in precipitation due to climate change will affect the availability of water resources. The effect of climate change on precipitation will vary by region. Climate change projections pictured below show change in average precipitation under two climate scenarios RCP 2.5 and RCP 8.5 (Figure 2). RCP 2.5 is a low-emissions scenario, in which oil use decreases and CO_2 emissions stay at today's level until 2020, then decrease and become negative by 2100 (Bjørnæs, n.d.). RCP 8.5 is a high-emissions scenario, which involves no policy changes to reduce emissions (Bjørnæs, n.d.) Figure 2 shows that precipitation is likely to increase at high latitudes while precipitation will vary at mid-latitudes where dry regions will likely become drier and wet regions will become wetter (IPCC, 2014a).

Figure 2: Change in Average Precipitation (1986-2005 to 2081-2100), under RCP 2.5 scenario (left) and RCP 8.5 scenario (right) (IPCC, 2014a).



In the same areas where precipitation is expected to decrease, the availability of surface water and ground water resources is expected to decrease further limiting water resources (IPCC, 2014c).

Along with increased temperature, climate change projections suggest that precipitation in the region is likely to decrease with winter rainfall decreasing by 20% by 2040 and 35% by 2069 in the Eastern Mediterranean, North Africa, and Levant region, (Lelieveld et al., 2012). Along with decreased precipitation, massive population growth and increased demand for irrigation are putting an increased strain on limited groundwater resources in the region and lead to water scarcity.

Climate Change Effects on Agriculture and Food Security

The effect of climate change on agriculture and food security is complicated and expected to vary widely by region. The majority of studies show a negative impact on crop yields with isolated positive effects at high latitudes (IPCC, 2014c). In temperate regions of Europe, climate change may extend the growing season and make new land suitable for agriculture, outweighing the negative effects of higher seasonal temperature (Olesen & Bindi, 2002). Meanwhile, in subtropical regions, over time the expected negative effect on crop yields is expected to significantly outweigh the positive effects of climate change. Figure 3 shows projected changes in crop yields due to climate change over the next century. While projections for 2010-2029 show relatively equal distribution between positive and negative yields, by 2090-2109 almost 80% of projections show decreases in yields (IPCC, 2014a).

Figure 3: Projected Impact of Climate Change on Agricultural Yields (IPCC, 2014a)

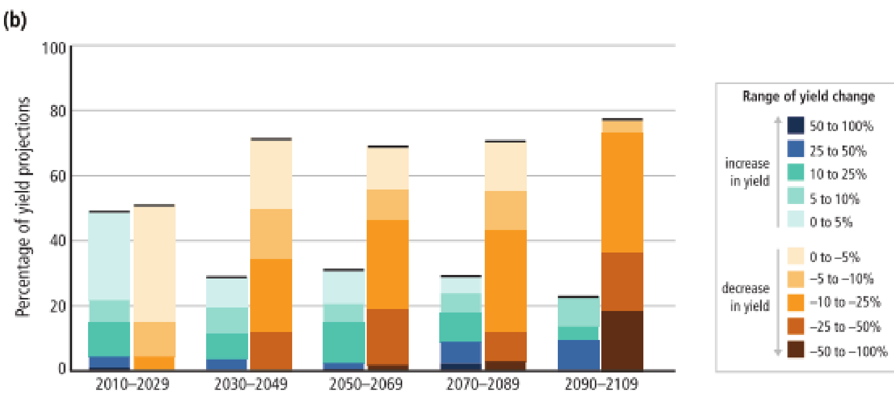


Figure SPM.9 | **(a)** Projected global redistribution of maximum catch potential of ~1000 exploited marine fish and invertebrate species. Projections compare the 10-year averages 2001–2010 and 2051–2060 using ocean conditions based on a single climate model under a moderate to high warming scenario, without analysis of potential impacts of overfishing or ocean acidification. **(b)** Summary of projected changes in crop yields (mostly wheat, maize, rice and soy), due to climate change over the 21st century. Data for each timeframe sum to 100%, indicating the percentage of projections showing yield increases versus decreases. The figure includes projections (based on 1090 data points) for different emission scenarios, for tropical and temperate regions and for adaptation and no-adaptation cases combined. Changes in crop yields are relative to late 20th century levels. *{Figure 2.6a, Figure 2.7}*

Food production in the Middle East is highly dependent on water resources with agriculture accounting for 84 percent of all water consumption (Bou-Zeid & El-Fedel, 2011). The Middle East already exceeded the water resources necessary to feed its population and imports food to meet demand (Allan, 1997). The combination of population growth and climate change could exacerbate the problem. For example, over the past 50 years the population of Jordan swelled by about 11 times. This massive population growth increased demands for agricultural products and the need for irrigated agriculture (Oroud, 2008). Subsequently, a large increase in irrigated agricultural land has increased demand for freshwater resources (Oroud, 2008). As a result of population growth and increased irrigation, annual per capita water availability has decreased from 3600m^3 in 1946 to just 160m^3 in 2004 (Jordan Ministry for Water and Irrigation & German Technical Cooperation, 2004). In other countries such as Morocco, Libya, Tunisia, and Syria, over 80% of freshwater withdrawal already goes to agriculture (Iglesias et al., 2007).

Extreme Weather and Drought

While it is difficult to attribute any particular extreme event to climate change, Climate change is expected to increase the intensity and frequency of extreme weather events (Worland, 2011). Climate change models predict that heat waves will become more frequent and intense (IPCC, 2014c). In many regions, extreme precipitation events are likely to occur more often and last longer (IPCC, 2014c). Climate change may already be causing extreme drought in the Middle East. By measuring tree rings, Cook et al., (2016) found that the recent drought between 1998 and 2012 was drier than any comparable period in the last 900 years and that the year 2000 was the single driest year in the region dating back to 1100 (Cook et al., 2016).

Figure 4: Case Study of Drought in Syria

An analysis of the impact of the 2007 to 2010 regional drought in Syria may give insight into how climate change may affect agricultural production and food security. Agriculture was a significant part of the pre-conflict Syrian economy, making up approximately 18% of GDP in 2007 (World Bank, 2017). Over two-thirds of cultivated land in Syria is rainfed with the remainder dependent on groundwater and irrigation. Severe drought, lasting approximately 3 years by some estimates, caused widespread water and agriculture insecurity (Kelley et al., 2015).

Case Study: 2008 Drought in Syria continued

The drought led to a 38 percent decrease in wheat production in Syria, which makes up 83% of all grain production in Syria(United States Department of Agriculture, 2008). The graph below shows the sharp drop in wheat production due to the 2007/2008 drought (United States Department of Agriculture, 2015)

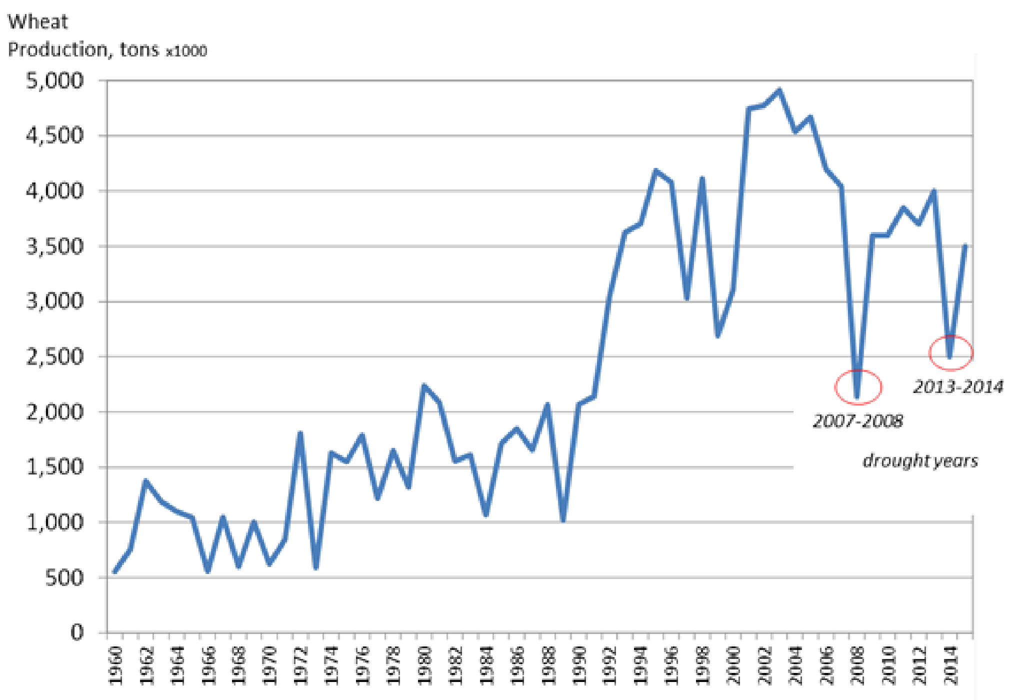


Figure 1. Syria wheat production from 1960 to 2015 (USDA Production, Supply and Demand database).

The shortage of wheat increased grain prices by 29% and forced Syria to deplete emergency reserves. Furthermore, Syria which had been food self-sufficient, imported wheat for the first time in 40 years (IRIN, 2009).

Massive migration associated with this drought may have exacerbated tensions that led to the ongoing Syrian conflict (Kelley et al., 2015). An estimated 1.5 million people migrated from rural agricultural areas to urban centers increasing strain on the poor services provided by the Assad government (Kelley et al., 2015).

Objective

Although extensive research has been conducted for Syria to better understand the current crisis, research has not been as extensive for Jordan. Thus, this study examines the impact of drought in Jordan, provides a comparative perspective with Syria, and assesses how climate change will affect the areas afflicted by drought.

I. Methods

To understand how drought affected Jordan several analyses were conducted. First, Jordan's current and past climate conditions were analyzed to understand overall climate patterns since 1900 and in particular to assess climate patterns leading up to the 2007-2010 regional drought. Next, a more detailed examination of the most recent drought was conducted to assess the severity of this drought, identify key areas that were affected and the impact this had on populations and agriculture production. Third, a comparison was made between Jordan and Syria to assess how the drought in Jordan differed from the Syria case study described above. Lastly, an assessment was made to determine how the region will likely be affected by climate change in the future.

1. Assess climate in Jordan past to present.

There are over 50 different indices used to measure drought (World Meteorological Organization & Global Water Partnership, 2016). These are based on meteorology variables such as temperature and amount of precipitation; soil moisture, hydrology (e.g. reservoir supply), remotely sensed information (e.g. amount of greenness and healthy vegetation (NDVI)), and crop data (World Meteorological Organization & Global Water Partnership, 2016). For the purpose of this study several of these variables were used including the standard precipitation index (SPI), Normalized Difference Vegetation Index, and a combination of four indices as part of the Composite Drought Index (CDI).

Jordan is an arid region with an average annual precipitation of 111 mm (The World Bank, 2017). It receives most of its rainfall between November and April which coincides with the growing season for winter crops including wheat and barley which are mostly rain fed and are thus most susceptible to yearly variation in rainfall (Hjort, Tamam, & Ghul, 1998). To best understand drought impact in Jordan, analysis focused solely on the winter months of November to April.

To assess whether the 2007-2010 regional drought affected Jordan and how this drought compared with historical droughts, a six month standard precipitation index was calculated for November to April from 1901 to 2012. This time period was used to evaluate drought frequency and to ensure that at least 30 years of data was used, the minimum recommended time series by the World Meteorological Organization (Joint Research Center, 2011). Monthly precipitation data for Jordan created by the Climatic Research Unit of the University of East Anglia and made publically available by the World Bank's Climate Knowledge Hub was obtained. The total monthly precipitation as well as the standard precipitation index for the winter season (November to April) for each year between 1901 and 2012 was calculated and used to assess drought frequency.

The standard precipitation index (SPI) is a simple index that measures the rarity of drought at a particular location and time period with just monthly precipitation data (World Meteorological Organization & Global Water Partnership, 2016). The SPI, originally developed in 1993 by scientists out of Colorado State University, was endorsed by the World Meteorological Organization as the main meteorological drought index that countries should use to monitor drought conditions in 2009 (World Meteorological Organization & Global Water Partnership, 2016). The SPI is calculated by "fitting a gamma probability density function to a given frequency distribution of precipitation totals for a given station (Colorado State University, n.d.)." Documentation of gamma distribution calculation and SPI calculation are outlined by Colorado State University (Colorado State University, n.d.).

SPI was calculated using, a free program from the National Drought Mitigation Center (National Drought Mitigation Center, n.d.). For the purpose of this study, SPI values were determined using the winter months (November to April). SPI values range from -3 to 3 and were classified based on the classification scheme used by the University of Nebraska Lincoln's Drought Monitor (University of Nebraska Lincoln, 2017) (Table 3). Drought years were identified when SPI values were less than or equal to -0.5.

Table 1: Standard Precipitation Index Classifications (University of Nebraska Lincoln, 2017).

SPI Value	Drought Classification
-0.5 to -0.7	Abnormally Dry
-0.8 to -1.2	Moderate Drought
-1.3 to -1.5	Severe Drought
-1.6 to -1.9	Extreme Drought
-2.0 or less	Exceptional Drought

2. Assess Severity of the most recent Drought

The composite drought index (CDI) was used to assess the severity of the recent drought between November 2008 and April 2009. While the standard precipitation index is an effective indicator for measuring meteorological drought, the CDI provides a more holistic approach. The CDI is a multivariate index which combines several factors considered to be important in the assessment of drought and include precipitation anomaly, vegetation anomaly, soil moisture anomaly, and land surface temperature anomaly into a single index (International Center for Biosaline Agriculture, 2016). The CDI was first used in Morocco by the University of Nebraska's National Drought Mitigation Center (National Drought Mitigation Center, 2015) as part of a larger Land Data assimilation systems project, in order to improve water resources management in preparation of climate change (National Drought Mitigation Center, 2015). Since then, the CDI, as part of a new drought early warning system, is currently being adapted for use throughout the Middle East region by the International Center for Biosaline Agriculture (International Center for Biosaline Agriculture, 2016). Although the methodology remains the same, the weighted formula described below is adjusted to each local context based on feedback from local stakeholders.

The CDI and the four input datasets used in this study were provided by the International Center for Biosaline Agriculture. Although recent CDI calculations are publically available on the MAWRED knowledge portal, the CDI calculations for 2008-2009 and input datasets were unavailable, so a request was made for the CDI and anomaly datasets for November 2008 to April 2009. The CDI and input datasets were provided in netcdf format and converted to a raster for visualization in ArcGIS. The Composite Drought Index was calculated for each month by ICBA using Equation 1 where each of the four variables were weighted using a Middle East regional weighting developed by ICBA, the University of Nebraska Lincoln, and NASA (Beragaoui, 2016). While normally this formula is adapted to the local context based on engagement with local stakeholders, consultations have not yet begun with stakeholders in Jordan and may change in the future (Beragaoui, 2016).

Equation 1: CDI = 0.40 * SPIa + 0.2 * SMa+ 0.2 * LSTa + 0.2 * NDVIa

Where SPIa = precipitation anomaly, SMa = soil moisture anomaly, LSTa = land surface temperature anomaly, and NDVIa = vegetation anomaly.

Vegetation Anomaly (NDVIa): Vegetation anomaly is calculated using the Normalized Difference Vegetation Index (NDVI) captured by the USGS MODIS Instrument. NDVI measures vegetation health along a scale of -1 to 1, where -1 to 0 is water, 0 to 0.1 is barren rock or soil, 0.2 to 0.5 is sparse vegetation, and >0.5 is considered dense vegetation (United States Geological Survey, 2015).

Land Surface Temperature Anomaly (LSTa): Land Surface Temperature anomaly is calculated using Land Surface Temperature data captured by the USGS MODIS instrument. LST measures soil temperature in degrees Kelvin (University of California Santa Barbara, n.d.).

Soil Moisture Anomaly (SMa): Soil Moisture anomaly is calculated using soil moisture data obtained from the Land Information System (LIS), NASA Goddard Space Flight Center. The data represents the amount of moisture/ water content in the soil. The LIS utilizes software engineering, computation technology and remote sensing to conduct high performance monitoring (see Peters-Lidard et al., 2007 for details) .

Precipitation Anomaly (SPIa): The standard precipitation index (SPI) was calculated using CHIRPS gridded precipitation data developed by the Climate Hazards Group at the University of California Santa Barbara(Climate Hazards Group, n.d.). CHIRPS uses a combination of remotely sensed data and ground observations, thus avoiding the limitations of using solely remotely sensed data which can underestimate extreme precipitation events and data gaps from ground station data which are irregularly spaced and often unavailable for rural areas (Climate Hazards Group, n.d.).

The details of each data source used for the CDI are summarized in Table 2.

Table 2: Summary of Datasets used in CDI Calculation

Anomaly Dataset	Description	Data Source	Timeframe	Spatial Resolution	CDI Weighting
Vegetation Anomaly (NDVIa)	Measures average monthly vegetation Health relative to the historical monthly average	International Center for Biosaline Agriculture	2002-2016	5km	0.2
Land Surface Temperature (LSTa) Anomaly	Captures surface temperature relative to the average monthly temperature	International Center for Biosaline Agriculture	2002-2016	5km	0.2
Standard Precipitation Index (SPIa) – Precipitation Anomaly	Measures precipitation relative to historical monthly precipitation	International Center for Biosaline Agriculture	1981-2016	5km	0.4
Soil Moisture (SMa) Anomaly	Captures whether soil moisture is drier or wetter than average	International Center for Biosaline Agriculture	2002-2016	5km	0.2

The anomaly for each month was determined by calculating the difference between precipitation, vegetation, soil moisture, and land surface temperature values of a given month compared to the historical average for these datasets respectively (Beragaoui, 2016). NDVIa, LSTa, and SMa anomalies were calculated for the period of 2002 to 2016, while SPIa was calculated for a longer period 1980-2016 based on data availability (Beragaoui, 2016). Each output was then normalized by assigning a pixel value ranging between -5 (exceptionally dry) and 5 (exceptionally wet) based on the percentile range (Beragaoui, 2016) listed in Table 3. These classifications match the drought severity classifications used at the U.S. Drought Monitor for Objective Drought Indicator Blends (University of Nebraska Lincoln, n.d.).

Table 3: Percentile Classifications for Composite Drought Index (Beragaoui, 2016)

Values	Percentiles	Classification
-5	0 to 2%	Exceptional Drought
-4	2 to 5%	Extreme Drought
-3	5 to 10%	Severe Drought
-2	10 to 20%	Moderate Drought
-1	20 to 30%	Abnormally Dry
0	30 to 70%	Normal
1	70 to 80%	Unusually Wet
2	80 to 90%	Very Wet
3	90 to 95%	Severely Wet
4	95 to 98%	Extremely Wet
5	98 to 100%	Exceptionally Wet

Finally, a mask was applied to exclude areas with low vegetation (NDVI value < 0.15) since these represent areas that are uninhabited or inhospitable for agriculture (Beragaoui, 2016).

3. Impact assessment on population and agriculture

Once the CDI was calculated, an assessment was conducted to identify populations affected by drought and the effects of drought on agriculture.

3.1 Population affected by the drought.

To assess the total population that was affected by the drought, the total population residing within each grid cell value with a CDI value between -1 to -5 was determined. Landscan (2010), a gridded population dataset, estimates the total number of people living in a 1km grid cell (Oak Ridge National Laboratories, n.d.). The data was created using spatial data and imagery analysis to disaggregate census data within an administrative boundary. The population data for the 2010 dataset was based on a mid-year national population estimate from the Geographic Studies Branch, US Bureau of Census (Oak Ridge National Laboratories, n.d.).

To calculate the population affected by drought a winter drought summary was produced that represented the average CDI that occurred at each location throughout Jordan. For the remainder of this study, this will be referred to as CDI-AVG. CDI data from ICBA is only available for a monthly timeframe therefore the average CDI value for each grid cell was calculated for the period of November 2008 to April 2009. Using an average of the CDI values across the six month period provides a more balanced measurement of the drought conditions which vary between months and allows for the exclusion of no data values which may have affected the drought analysis for a particular month. Zonal Statistics were used to calculate the total population for each CDI-AVG value.

3.2 Drought effect on Agriculture.

The impact of drought on agriculture was assessed using a spatial approach to measure cropland affected and a non-spatial analysis of crop production data. To measure cropland affected, cropland was identified using MODIS Land Cover, a global dataset of dominant land cover from the Global Landcover Facility of the University of Maryland at a 500 meter resolution. The MODIS Land Cover dataset classified the dominant land cover for each pixel into one of 16 types including grasslands, savannas, cropland, barren rock and various types of forest (University of Maryland, 2017). The dataset for 2009 was used for this study to match the time period of the CDI analysis. A set of four images that covered Jordan were obtained and mosaicked; once mosaicked, the data was reclassified to include only cropland. The total area of cropland affected by the drought was estimated using average NDVI anomaly for November 2008 to April 2009. For the remainder of this study, this will be referred to as NDVIa-AVG. NDVIa-AVG was calculated by taking an average of the monthly NDVI anomaly values for

November to April. For each pixel of cropland the corresponding anomaly value from the NDVIa-AVG raster was identified.

In addition, to the spatial approach, crop production data from the Food and Agriculture Organization was used to examine how crop production may have been affected by drought. FAOSTAT is a global database of food and agriculture data at the country level (Food and Agriculture Organization, 2017). The database can be queried to specifications including indicator, type of crop, time period, and country and is exported as a csv file.

Although, fruits and vegetables are Jordan's main crops, these are primarily produced using irrigation. Therefore this study focused on the impact of drought on rainfed crops including wheat and barley. Data for yearly production in metric tons, area harvested in hectares, and yield in hectograms per hectare for wheat and barley, was obtained for 1960 to 2014 to assess historical trends in production. A direct comparison between 2010, a year with good precipitation, and 2009 was performed.

4. Comparison with Syria

In order to assess historic drought conditions in Syria, a six month standard precipitation index was calculated for each winter (November to April) between 1901 and 2012. This analysis follows the same methods used for Jordan in section 1. It was used to contrast the severity of the 2007-2010 regional drought across Jordan and Syria and see how the 2008-2009 drought analyzed in detail for Jordan fits into historical drought conditions in Syria. Second the composite drought index from section 2 was used to directly compare the severity of the 2008-2009 drought across Jordan and Syria. Finally, historic crop production data from FAOSTAT was used to assess how wheat production in Syria was impacted by the 2008-2009 drought in comparison with Jordan.

5. Future Assessments of Drought in Jordan

To assess future vulnerability of areas that were affected by the 2008-2009 winter drought, climate change data was assessed to determine how average monthly precipitation and average max temperature will likely change under future climate scenarios. For this part of the study, the month with the most severe drought condition was selected. Based on preliminary analyses, January 2009 experienced the most severe drought conditions and was analyzed in further detail.

Climate change modeling is dependent on future climate scenarios and the general circulation model. Representative Concentration Pathways are the newest scenarios used by the IPCC which describe potential futures for the main drivers of climate change including greenhouse gas emissions (Bjørnæs, n.d.). For this study, the RCP 4.5 scenario, which represents a significant reductions in greenhouse gas emissions and the RCP 8.5 scenario, which involves no policy changes to reduce emissions were selected (Bjørnæs, n.d.), were selected to represent the two extremes. The most relevant general circulation models for the Middle East were selected. Evans (2009) evaluated the 18 GCMs that were part of the 4th IPCC assessment report, to assess their performance and predictions for the Middle East Region against observational datasets for the late 20th and early 21st century and found that the best models for modeling precipitation were NCAR-CCSM 3.0, MIUB-Echo-G, and MRI-CGCM2.3.2a., while all of the models except PCM and BCC were fairly accurate for temperature. Furthermore for precipitation, he found that the multi-model mean outperformed all but one individual model (Evans, 2009). Data for mean monthly maximum temperature, rainfall and mean monthly average temperature were obtained from WorldClim at 30 second resolution for the RCP 4.5 and 8.5 scenarios (2040-2050) and historical data (1960-1990) for January. The downscaled climate data for the models identified by Evans (2009) was not available. Instead the average of six models (Table 4), including CCSM4 and MRI-CGCM3, all of which are updated versions of the models evaluated in the Evans (2009) study was used.

Table 4 – GCMs used to evaluate climate change effects in Jordan

Model	Source
CCSM4	National Center for Atmospheric Research
CNRM-CM5	National Center for Meteorological Research
GFDL-CM3	Geophysical Fluids Dynamics Lab
HADGEM2-ES	Met Office Hadley Centre
GISS-E2-R	National Aeronautics and Space Administration - Goddard Insitute for Space Studies
MRI-CGCM3	Meteorological Research Institute

First, the percent change in monthly mean average precipitation for January between 1960-1990 and the average rainfall of the six GCMs 2040-2060 for RCP4.5 was calculated. This was repeated using the average rainfall of the six GCMs 2040-2060 for RCP8.5.

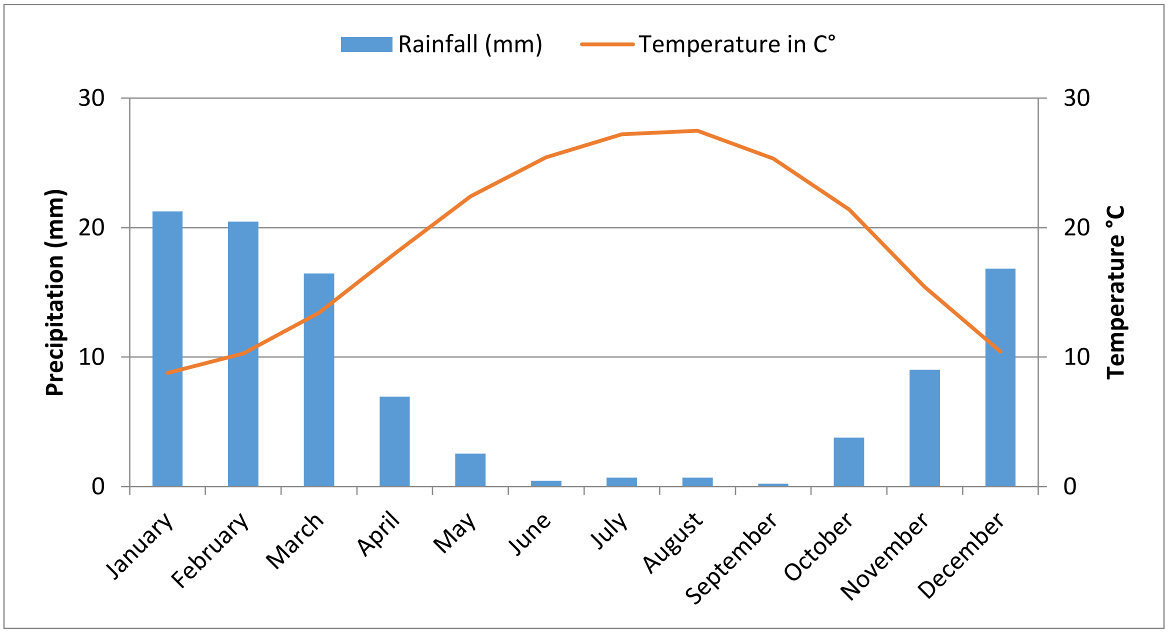
The same process was used to calculate the change in average max temperature for January between 1960-1990 and 2040-2060 with one key difference. Instead of calculating percent change, the raw difference in temperature was used.

IV. Results

Assessment of Current Climate and Historic Drought Conditions

Jordan is characterized by a hot dry summer (monthly average temperature =26°C; monthly average precipitation 0.5mm between June and September) and cooler wetter winters (monthly average temperature 13 °C; monthly average precipitation ranging between 7-22 mm between November and April) (Figure 5). The majority of Jordan's rainfall occurs between November and April, with very little rainfall during the summer months.

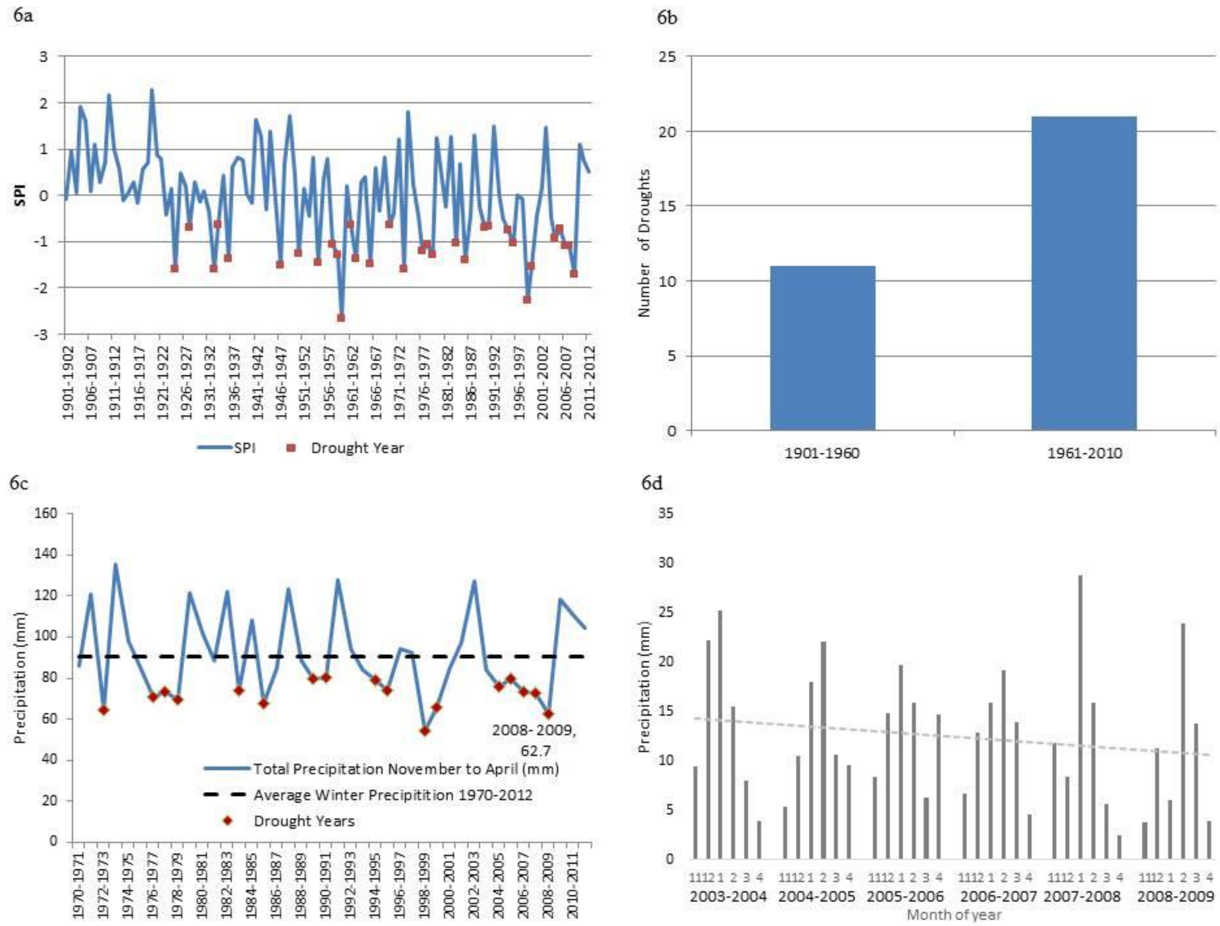
Figure 5: Average Monthly Precipitation and Temperature in Jordan 1970 - 2012



Since 1900, Jordan has had a total of 33 winter droughts, years where SPI was less than -0.5 (<79mm of precipitation) (Figure 6a). There were almost twice as many winter droughts from 1961-2010 as occurred between 1901 and 1960 (Figure 6b).

Since 1970, Jordan has had 17 winter droughts, years where the SPI was less than -0.5 (< 79mm of precipitation) (1972-1973; 1976-1979; 1983-1984; 1985-1986; 1989-1991; 1994-1996; 1998-2000, and 2004-2009) (Figure 6c). The country has experienced several prolonged droughts where drought conditions have persisted for two or more years. Between 1976 and 1979, Jordan experienced three consecutive seasons of moderate to abnormal drought conditions. Between 1998 and 2000, Jordan faced two consecutive seasons of severe to exceptional drought conditions. During the winter of November 1998 to April 1999, Jordan received just 54.4mm of precipitation, the lowest recorded precipitation between 1971 and 2012 and the second lowest since 1900 (Figure 6c). The six-month SPI value (-2.27) demonstrates that this was an exceptional drought (Table 1). Most recently, there was a period of five consecutive years of winter drought between 2004 and 2009 (Figure 6c). Precipitation reached a low of 62.7mm during the winter of 2008-2009. The SPI for the winter of 2008-2009 was -1.71, classified as an extreme drought (Table 1). Figure 6d shows that while there is an overall downward trend in precipitation between 2004 and 2009 and that there is significant variation in precipitation between months. Between 2003 and 2008 Jordan received the most precipitation in January, but in the recent 2008-2009 winter precipitation in January was way below normal (Figure 6d).

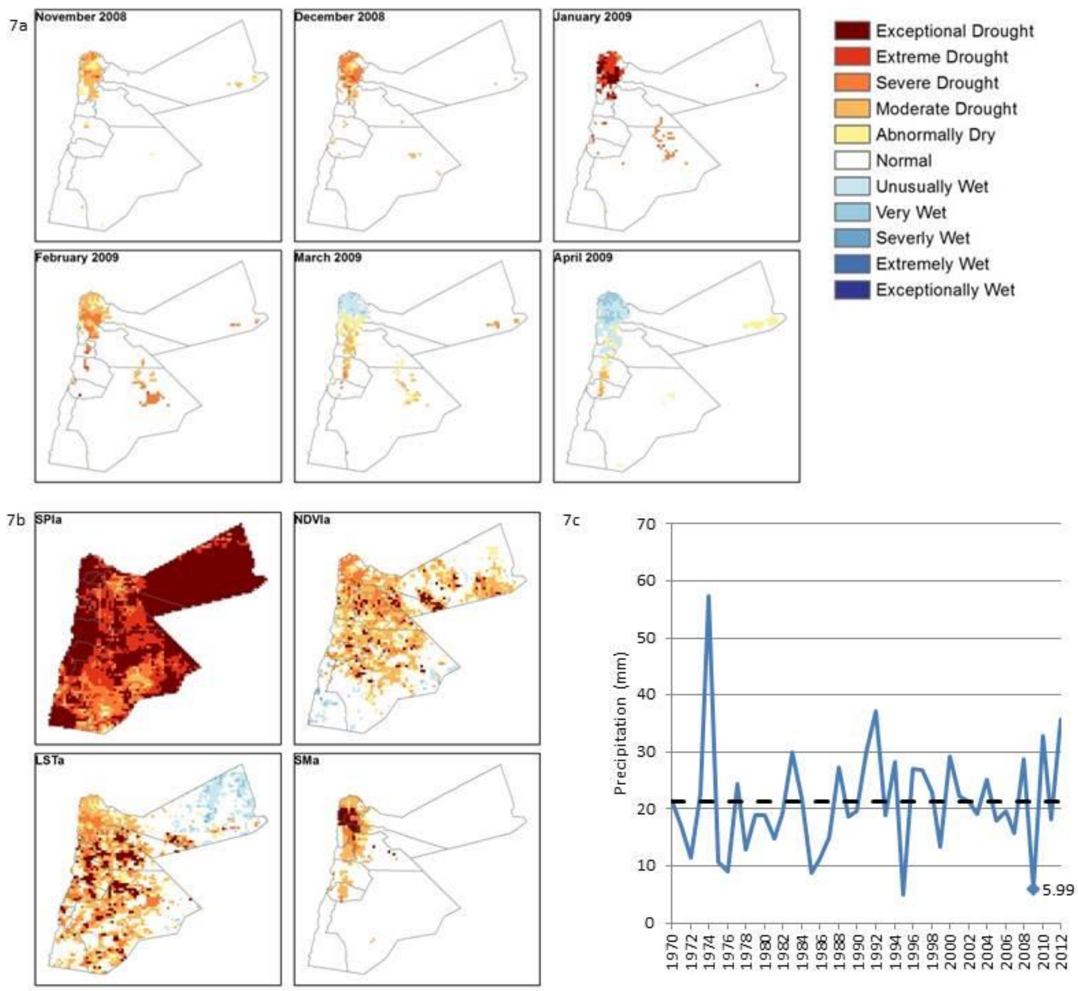
Figure 6: (a) Six Month Standard Precipitation Index (November to April) 1901 to 2012, (b) Winter Droughts 1901-1960 and 1961-2012, (c) Total Precipitation during the winter season (November to April) between 1971 and 2012, (d) Precipitation for November to April from 2003/2004 to 2008/2009



Drought Index

Drought conditions were found to be moderate to exceptional in northwest Jordan from November 2008 to February 2009, but drought conditions were alleviated by March and April (Figure 7a). January 2009 had the worst drought conditions with extreme and exceptional drought conditions in northwest Jordan. All four anomaly dataset show that Jordan experienced drought conditions in January 2009. Notably precipitation and soil moisture were exceptionally low in northwest Jordan. (Figure7b). Total Precipitation in Jordan was exceptionally low with an average of just 5.99 millimeters of precipitation compared to the historic average of 21.25 millimeters in January (Figure 7c).

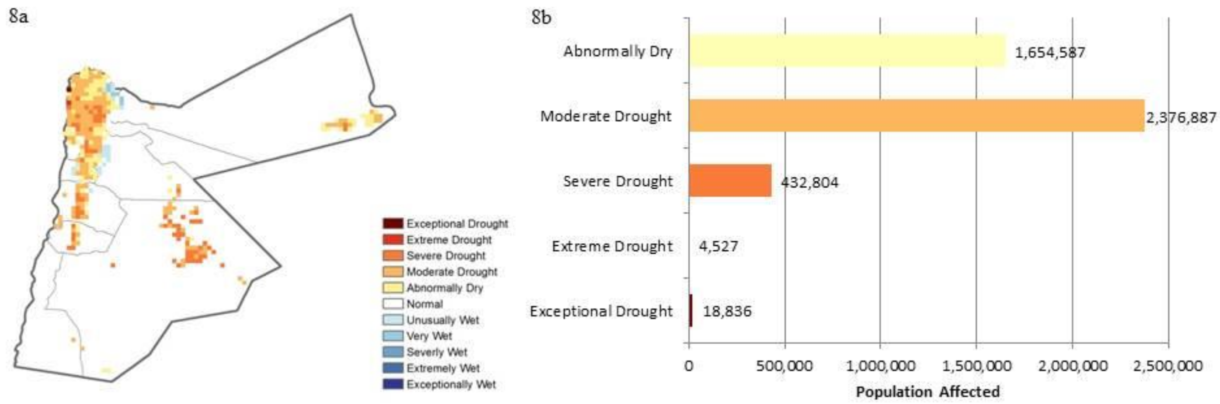
Figure 7: (a) Maps illustrating the spatial and temporal variation of the Composite Drought Index from November 2008 to January 2009, (b) Maps of Precipitation Anomaly (SPIa), Vegetation Anomaly (NDVIa), Land Surface Temperature Anomaly (SMa), and Soil Moisture Anomaly (SMa) for January 2009, (c) Monthly Precipitation in January 1970 to 2012.



Population and Agriculture Affected

The areas affected by drought overlapped with areas where the majority of Jordan's population resides (Figure 8a) where an estimated 4.7 million people, 73% of Jordan's population, reside.. The total number of people affected by average CDI classification ranged from abnormally dry (20-30%) to exceptional drought (0-2%) (Table 4).

Figure 8: (a) Map of Average Composite Drought Index (CDI-AVG), November 2008 to April 2009, (b) Populations affected by drought November 2008 to April 2009.



Jordan's cropland is primarily located in the northwest part of the country (Figure 9a). Although CDI-AVG (Figure 9a) shows that most of the northwest was affected by the drought, NDVI-AVG shows that vegetation health was not as badly affected as the other input variables (Figure 9a). NDVI anomaly values show that vegetation ranged from moderate low to abnormally high. 52 % of Jordan's cropland was negatively impacted by the drought (Figure 9b).

Figure 9a: Maps of Cropland and NDVI-AVG (November 2008 to April 2009)

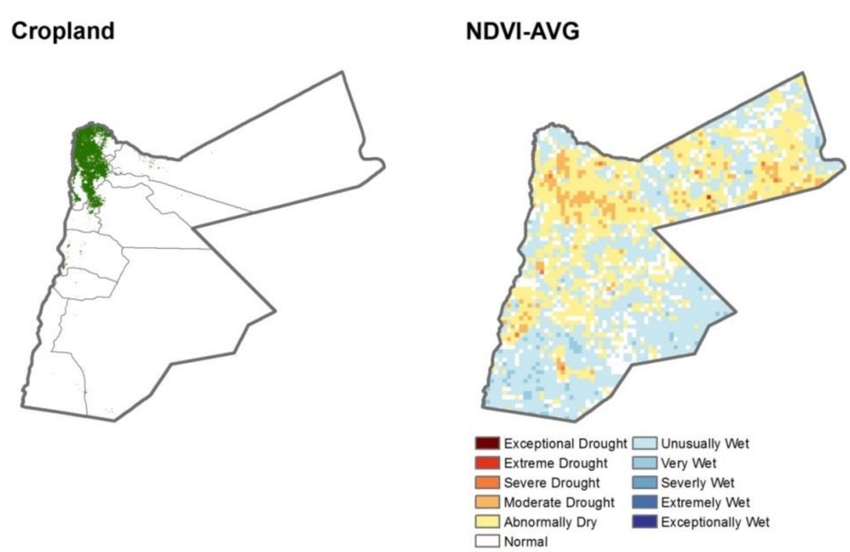
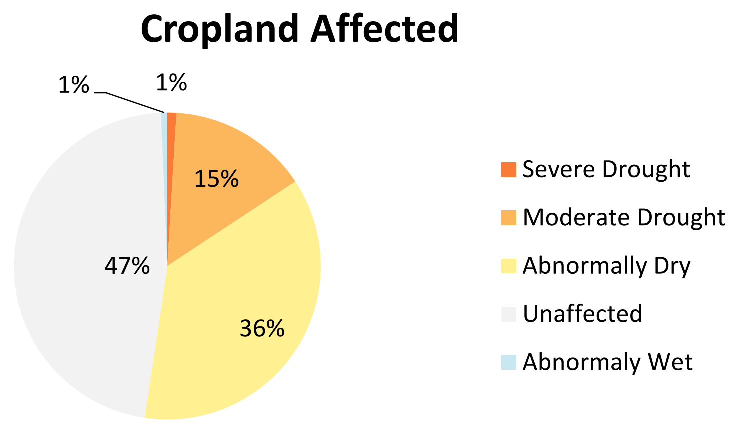


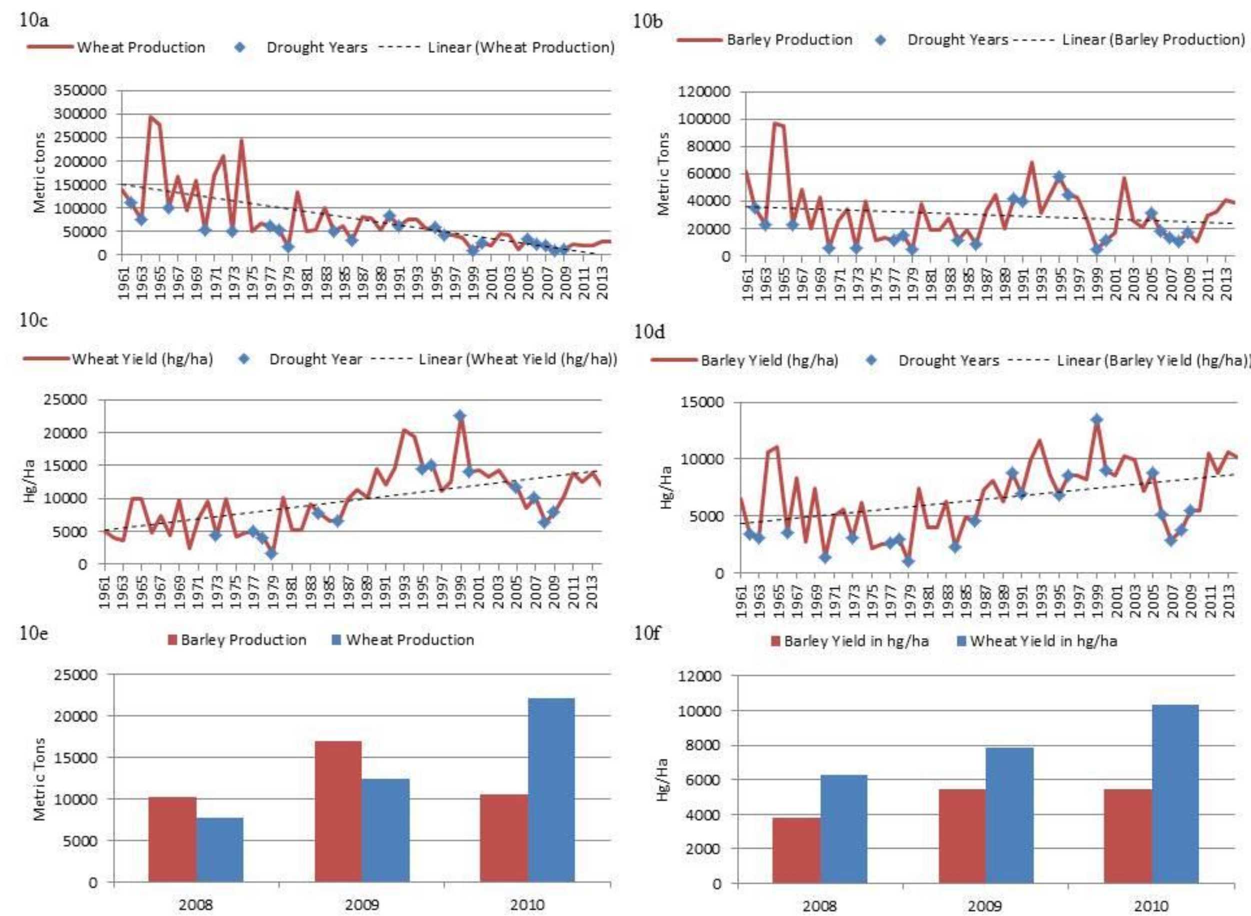
Figure 9b: Cropland Affected, Percent of Cropland affected by Average NDVI Anomaly classification ranging from abnormally wet (70-80%) to exceptional drought (0-2%)



Jordan has experienced a historic decrease in wheat and barley production since the 1960s (Figure 10a and 10b). Meanwhile the yield, amount of wheat produced per hectare, has increased historically (Figure 10c and 10d).

Comparison of wheat and barley production and yield in 2009 with 2008 and 2010 (Figure 10e and 10f) does not reveal a clear relationship between barley and wheat production and drought severity. Even though winter 2009 had worse drought conditions than 2008, production and yield of wheat was actually higher in 2009 than 2008. It does seem however that wheat production and yield were higher in 2010 (a non-drought year). Barley production and yield reacted differently than wheat. Despite being a worse drought season, barley production and yield in 2009 was higher than both 2008 and 2010.

Figure 10: (a) Wheat Production per Year in Metric Tons, (b) Barley Production per Year in Metric Tons, (c) Wheat Yield in (hg/ha), (d) Barley Yield in (hg/ha), (e) Wheat and Barley Production in Metric Tons , (f) Wheat and Barley Yield in Hectograms per Hectare



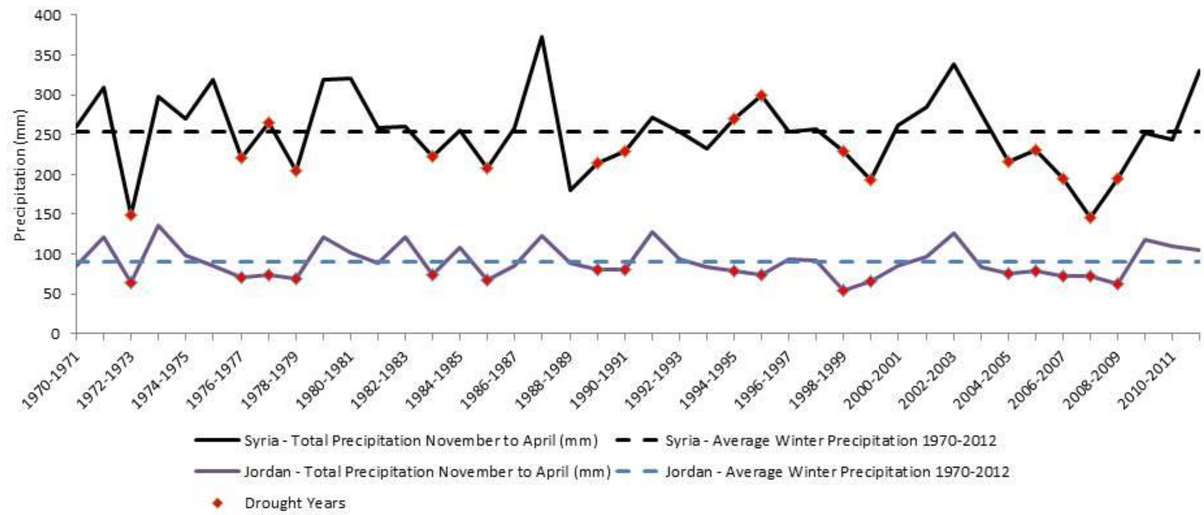
Comparison with Syria

Although Syria follows a similar climate pattern as Jordan with the hot drier summers and wetter cooler winters it receives over twice as much precipitation as Jordan with an average of approximately 252 millimeters per year (The World Bank, 2017).

Drought years in Syria largely mirrored those in Jordan with winter droughts in the same years (Figure 11a). As in Jordan, Syria experienced five consecutive years of winter drought between 2004 and 2009 and also suffered an extreme drought in winter 2008-2009 (SPI value of -1.61) (Figure 11b). Although total winter rainfall in Syria (145 to 215 mm) remained much higher than Jordan (62 to 80mm) (Figure 7a), drought conditions were more severe in Syria in relative terms. Syria was hit with three consecutive years of severe to exceptional winter drought between 2006 and 2009 (Figure 7b). The severity of the 2008-2009 drought in Syria was nearly identical to Jordan, but in the winter of 2007-2008 Syria experienced an exceptional drought. The winter of 2007-2008 in Syria had the lowest total precipitation of any winter between 1901 and 2012, over 100 millimeters below average.

Figure 11: (a) Syria – Jordan Comparison - Winter Precipitation November to April, (b) Syria – Jordan Comparison of Standard 6-Month Standard Precipitation Index (November to April) 2004 to 2009

11a



11b

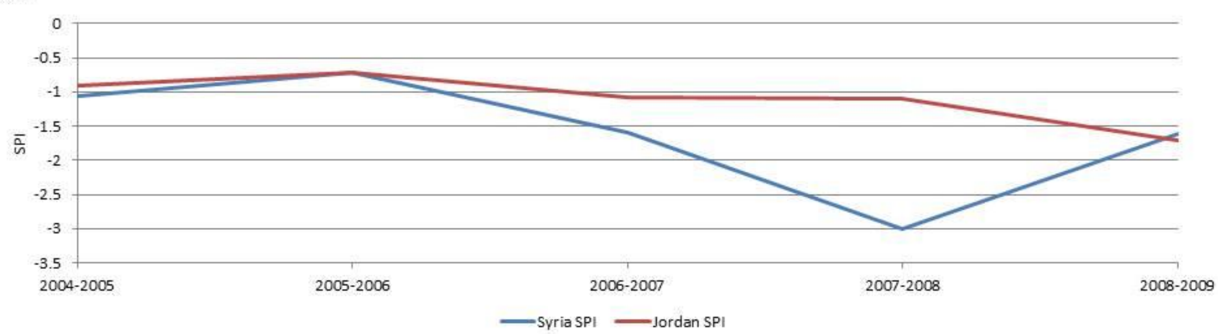
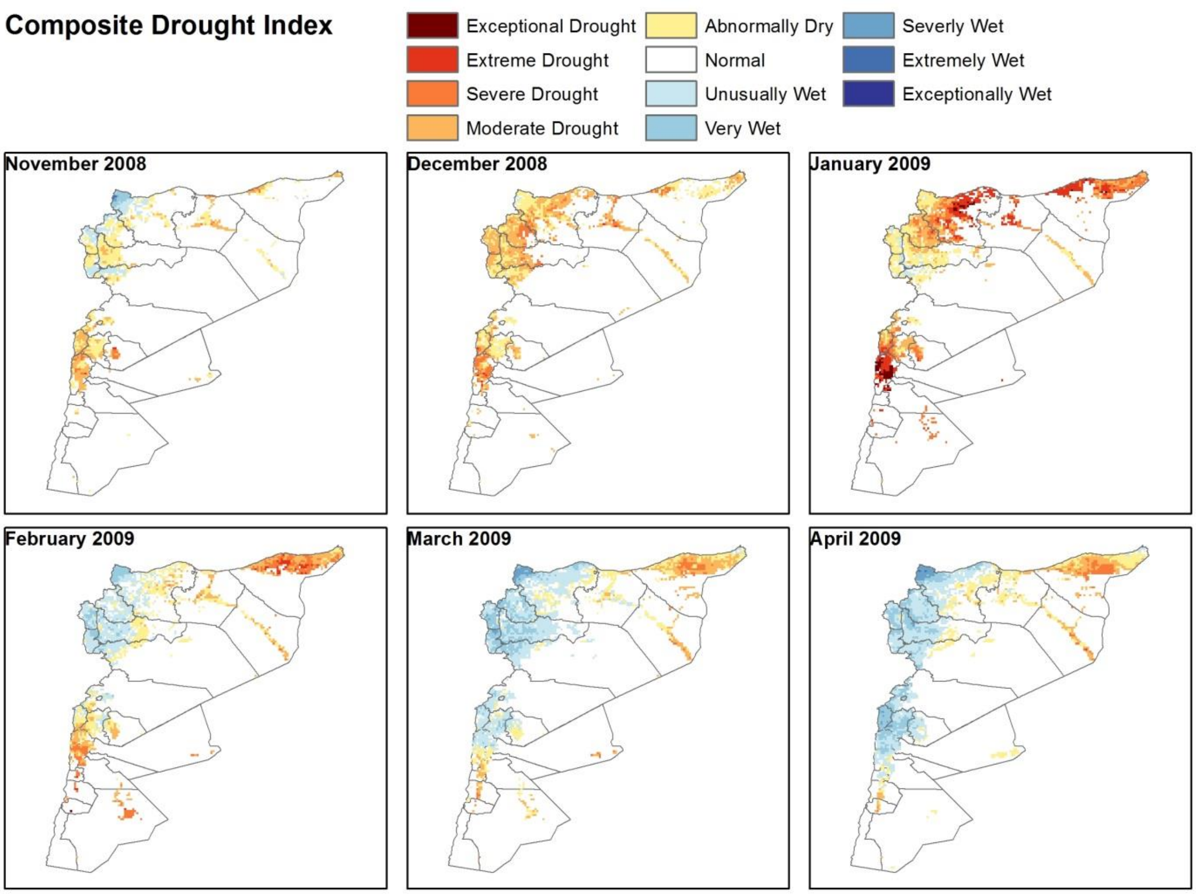


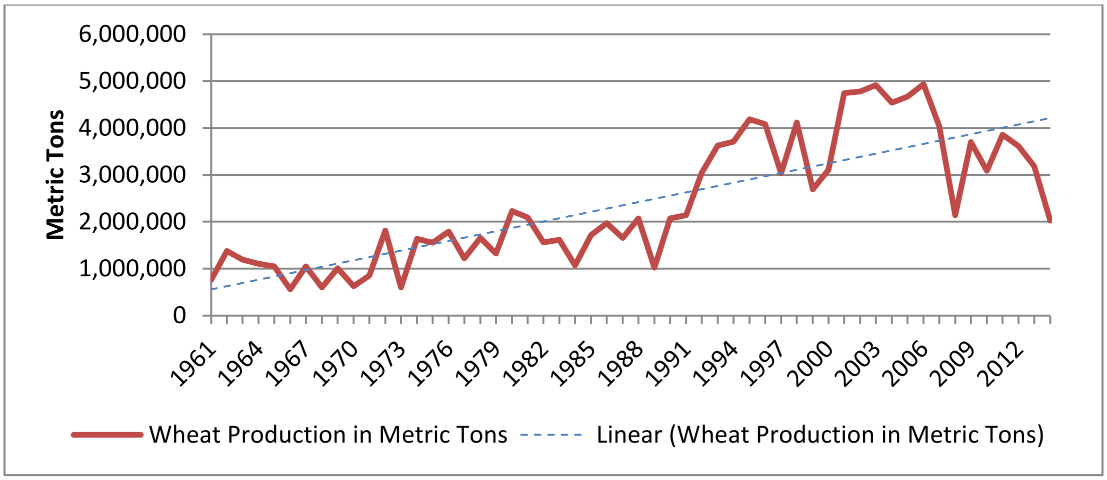
Figure 12 shows the composite drought index across Jordan and Syria for winter 2008-2009. In contrast with Jordan, the drought impacted several different agricultural regions in different ways. Southwest Syria experienced drought conditions from November to January, while northwest Syria experienced drought conditions primarily in December and January, while drought conditions lasted from December to April in northeast Syria. Drought conditions were most severe in January 2009 across both countries.

Figure 12: Composite Drought Index 2008-2009 Syria – Jordan Comparison



Wheat production in Syria dwarfs production in Jordan. Between 2000 and 2014, Syria produced an average of 3.8 million metric tons of wheat per year compared with an average of 24 thousands metric tons of wheat produced on average in Jordan during the same period. In contrast with Jordan which has experienced a historic decrease in wheat production, Syria has experienced a historic increase in wheat production since 1960 (figure 13). Wheat production in 2009 was just over 3.7 million tons, slightly below the average since 2000.

Figure 13: Wheat Production in Syria 1960-2014

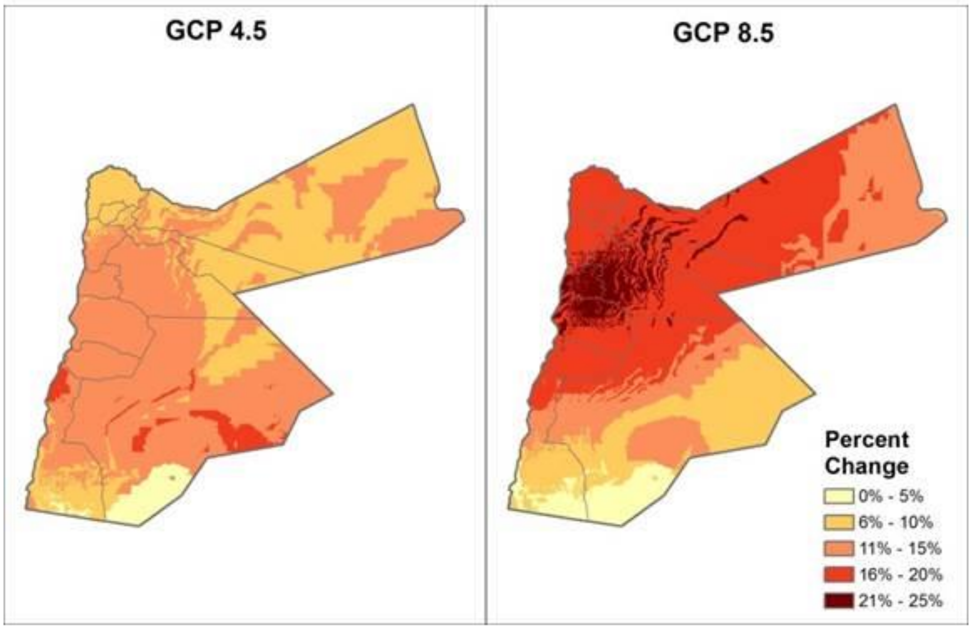


Future Assessments of Drought in Jordan

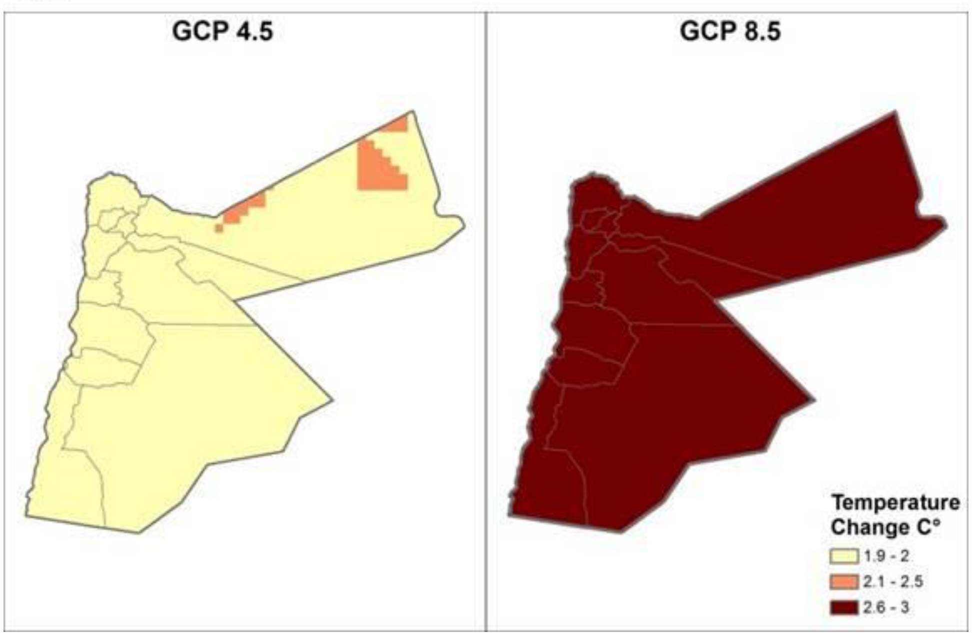
Average January precipitation will decrease in both low and high emissions scenarios. Northwest Jordan, which averages between 80 to 120 millimeters, is likely to see a decrease of 5-10% in precipitation under RCP 4.5 (low emissions scenario) and a 16-20% decrease under RCP 8.5 (high emissions scenario) by 2050 (Figure 14a). Max temperature in January will likely increase by 2 to 3 degrees Celsius under both RCP 4.5 and RCP 8.5 scenarios (Figure 14b). The average max temperature in January for the current climate (1960-1990) is 21.2 degrees Celsius, so while a 2 to 3 degree increase is significant, this is unlikely to have a major effect on winter crop production on its own.

Figure 14: (a) Percent Change in Average January Monthly Precipitation in GCP 4.5 and GCP 8.5 Scenarios, (b) Change in Max Temperature in January 1960-1990 to 2040-2060 in GCP 4.5 and GCP 8.5 Scenarios

14a



14b



V. Discussion

This study highlights the increasing frequency and severity of drought conditions in Jordan. With almost twice as many droughts between 1961-2012 as between 1900 and 1960, drought frequency is increasing in Jordan. This finding expands upon regional analysis of drought that found that the period of 1998 to 2012 was the driest in the past 900 years (Kelley et all) and that the Mediterranean has experienced ten of the driest winters within the last 20 years (Hoerling et al., 2012). This trend coupled with future climate trends that show an increase in max temperature and decrease in winter precipitation emphasize that water scarcity is likely to become an even greater concern for future generations.

Analysis of the 2008-2009 drought revealed that drought conditions during the winter season were extreme. Normally January is one of Jordan's wettest months but during the 2008-2009 drought Jordan received an average of just 6 millimeters of rainfall compared to an average of 22 millimeters (Figure 3c). The study found that drought primarily affects northwest Jordan which coincides with the areas where the majority of Jordan's population resides and where its cropland is primarily located. This does not come as a surprise given that large areas of the country are barren or desert with little to no precipitation or vegetation.

The most surprising result of this analysis was the lack of a clear relationship between drought severity and production of wheat and barley in Jordan. There are a number of factors that requires more investigation beyond this study. An analysis of the CDI maps for winter 2007-2008 and 2009-2010 along with more detailed landcover, that specifically identifies areas of wheat and barley cropping areas, could reveal spatial and temporal differences between these droughts that explain why production was lower in the winter of 2007-2008. It is possible that farmers in 2008-2009 improved adaptation methods such as using more drought resistant seed varieties or that other factors such as disease, insects or weeds affected production (Curtis, n.d.).

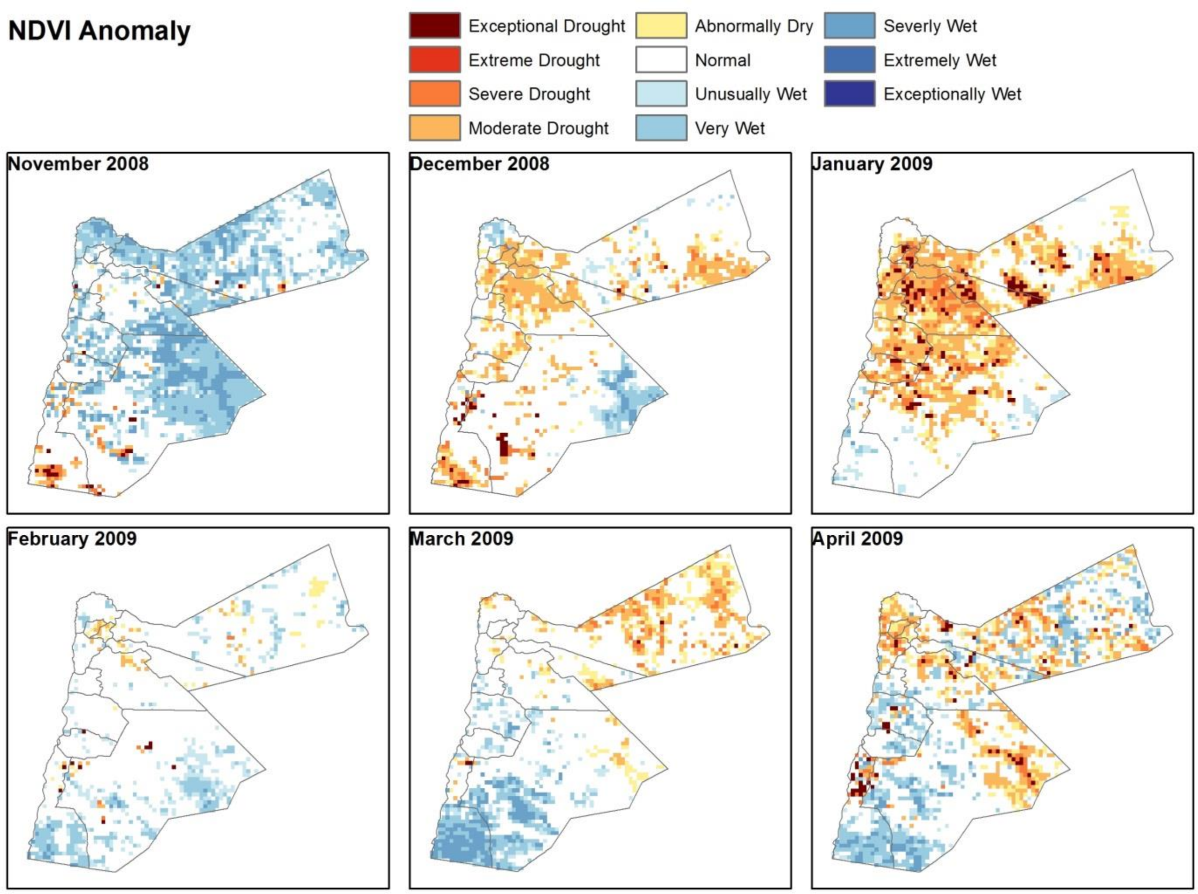
Climate change projections suggested that max monthly temperature would increase and average precipitation would decrease in January. Asseng et al, 2015 examined the effect of mean seasonal temperature on wheat production. Globally for each degree celcius (°C) increase in temperature global wheat production is expected to fall by 6% (Asseng et al., 2015). The optimum growing temperature for wheat is about 25 °C (Curtis, n.d.). This suggests that an increase in max temperature in January to 23 or 24 °C on its own may actually improve wheat production in Jordan. Increased temperature early in the growing season can have a positive effect on wheat production while increased temperature late in the growing season can have negative effects as maturity dates are move up (Asseng et al., 2015). A decrease in precipitation may have a variety of effects beyond a decrease in production. Farmers may shift to more drought resistant varieties, increase use of irrigation, or shift to other crops altogether. Further research is needed to understand how climate change will impact temperature in May and June, at the end of the wheat growing season and to determine how farmers have adapted to increased drought frequency in other areas.

Although Syria and Jordan both experienced five consecutive years of drought between 2004 and 2009, key differences between Syria and Jordan may explain why the drought created instability in Syria while Jordan remained stable. While Syria receives much more rainfall that Jordan on average, the drought between 2004 and 2009 was more severe in relative terms. The winter of 2008-2009 had an almost identical standard precipitation index across countries, but Syria experienced an exceptional drought in 2007-2008 which was the driest winter in the past century. During the 2007-2008 winter, wheat production dropped to about 2.14 million metric tons compared to the average of 3.8 million metric tons between 2000 and 2014 (Food and Agriculture Organization, 2017). Another key difference between Syria and Jordan is the importance of domestic grain production. Wheat production in Syria is over 150 times greater than in Jordan and that most of the wheat consumed in Syria is produced internally (Food and Agriculture Organization, 2017). Prior to the drought Syria was a net exporter of wheat with a self-sustainability rate of 1.21 while Jordan was already dependent on imports with a self-sustainability rate of just 1.81 (Arab Organization for Development, 2014). While it is positive that Syria is more food self-sufficient than Jordan, this dependence on domestic production means that drought has a greater impact. By 2010, Syria wheat self-sustainability rate fell to 74.1 and the country was forced to import wheat (Arab Organization for Development, 2014). There was also a significant drop in wheat production in Jordan in 2007-2008, just 7.8 thousand metric tons compared to an average of 24 thousand metric tons (Food and Agriculture Organization, 2017), but in absolute terms this decrease was much smaller compared to Syria. This may explain why the decrease in wheat production in led to instability in Syria and not in Jordan. The importance of wheat both as a livelihood and food staple in Syria, continues to make wheat a key resource coveted by opposing factions in the civil war (Ciezadlo, 2015).

Measuring the impact of drought on agriculture was more complex than anticipated and this study suffered from several research and data limitations. Although the composite drought index provides a more holistic approach to identifying drought conditions, it may overestimate the impact of drought on agriculture by overemphasizing factors that may not affect some agricultural land. For example, irrigated cropland is unlikely to be significantly impacted by a decrease precipitation unless the availability of groundwater is affected. An initial analysis used the composite drought index to measure cropland affected, showing that over 90% of cropland had been affected by the drought. Instead the NDVI anomaly, which is a direct measure of vegetation health, on its own may be a better measure as it more accurately measures the impact of drought on agricultural land and highlights key geographical differences. For example, vegetation in the Jordan valley, along Jordan's northwest border, was less impacted than the northwestern highlands (Figure 9a, Figure 15 – check Figure Numbers). Furthermore, the 5 kilometer resolution at which the composite drought index and vegetation anomaly data were calculated may ignore more local differences in drought impact. Unfortunately, the composite drought index cannot be produced with the current data inputs at a higher resolution because the precipitation data from CHIRPS is only available at 5km resolution. NDVI anomaly alone could be calculated at a higher resolution to identify more localized differences in how cropland reacted to drought conditions.

The NDVI-AVG was a better indicator for measuring the effect of drought on cropland, but may still overestimate the impact of the drought. NDVI anomaly shows normal and slightly wet conditions from November to March 2009, while drought conditions in northwest Jordan didn't emerge until April 2009 (Figure 15).

Figure 15: NDVI Anomaly by Month for Jordan between November 2008 and April 2009.



Although Jordan contains a mix of rain fed and irrigated agricultural regions, the land cover data used in this study does not make the distinction between that rainfed and irrigated cropland. Rain-fed agriculture is most common in the mountainous areas and highlands of northwest Jordan (Ababsa & Demilecamps, 2013) and are generally smaller family farms that grow grains, olives, and some assorted fruits and vegetables (Hjort et al., 1998). Jordan's irrigated agriculture is generally found in larger commercial farms in the Jordan valley and produce most of Jordan's fruit and vegetables including tomatoes, Jordan's main agricultural export (Ababsa & Demilecamps, 2013).This spatial pattern when assessed along with the NDVI-AVG (Figure 9a) suggests that the majority of cropland impacted would have been rain fed.

VI. Conclusion

This study highlights the impact of drought and climate change in Jordan and provides a comparative perspective with Syria. With an arid climate and little renewable water resources, drought and climate change are serious concerns for Jordan's water security. Drought frequency and severity are increasing and future increases in temperature and decreases in precipitation may exacerbate this trend. Drought occurs during the winter wet season and impacts northwest Jordan where the majority of Jordan's cropland is located and much of its population resides. While research suggests that rain fed crops such as barley and wheat are most susceptible to drought, further research is needed to explore why a clear relationship could not be identified between drought severity and production of these crops. Although Jordan was impacted by the same drought as Syria between 2005 and 2009, the drought was most severe in Syria during the winter of 2007-2008 rather than 2008-2009 analyzed in Jordan. The drought was much less severe in relative terms in Jordan and had a smaller impact on agriculture due to Jordan's historic decrease in production of these crops and increased reliance on imports.

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Appendix

Table 1. Summary of all data sources used in this study.

Data	Timeframe	Description	Spatial Resolution	Data Source
Monthly Precipitation	1971-2016	Monthly Average precipitation data. Used data for November to April	Non-spatial	World Bank Climate Hub
Composite Drought Index	November 2008 to April 2009	Index of drought severity based on NDVI, SPI, surface temperature anomaly, and soil moisture.	.05 degree	MAWRED Knowledge Hub- Interantional Center for Biosaline Agriculture
Landcover	2009	Landcover data used to identify cropland	.5km	Global Landcover Facility
Normalized Difference Vegetation Index Anomaly	November 2008 to April 2009	Input Variable for CDI, used in measuring cropland affected	.05 degree	MAWRED Knowledge Hub- Interantional Center for Biosaline Agriculture
Wheat Yield, area harvested	2000-2014	Annual production figures for agricultural products	Non-spatial	Food and Agriculture Organization (FAO)
Barley Yield, area harvested	2000-2014	Annual production figures for agricultural products	Non-spatial	Food and Agriculture Organization (FAO)
Landscan	2010	Gridded Population Dataset	1km	Oak Ridge National Library
Future Climate - Monthly Precipitation - January	2040-2060	Average values from six GCMS in rcp 4.5 and 8.5 scenarios	30 seconds	WorldClim
Future Climate -Max Monthly Temperature - January	2040-2061	Average values from six GCMS in rcp 4.5 and 8.5 scenarios	30 seconds	WorldClim
Historical Average - Monthly Precipitation	1960-1990	Interpolations of observed climate data	30 seconds	WorldClim
Historical Average - Max Monthly Temperature - January	1960-1991	Interpolations of observed climate data	30 seconds	WorldClim