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Water scarcity impacts on global food production

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ABSTRACT

In this review paper we focus on the dilemma of whether or not current fresh water supply will meet the demand/needs of agricultural crops despite the continuing impact of water scarcity. In addition, we evaluate whether an increase in future population, change in water demand and supply patterns, due to climate change, will allow sustainable food production. With increased scarcity of freshwater, new water conservation technologies and biotechnology were developed, as well as newly developed water sources such as recycled wastewater, and various water institutions, which may help ease water scarcity. With new advancements in farming practices and crop innovations global food supply is still challenged by climate change effects on both water and land resources used for food production.

1. Introduction

With population growth and rise in household income, the demand for food is estimated to increase by 70–100 percent by 2050 (USDA, n.d). With population growing and a rise in income, there is an increasing concern of whether or not current available resources will meet future food demand. Concerns exist in regards to resources such as land and water, proper technological advancements and farming practices, and adequacy of international trade agreements. While all these aspects would rather be best addressed jointly, this paper mainly focuses on how different technological advancements could help food production adapt to climate change and water scarcity.

We use the FAO (2002) definition of food security, utilized by Schmidhuber and Tubiello (2007), in which food security is a ‘situation that exists when all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy life.” Food security is a combination of several factors, including food availability (production and trade), access, stability of supply, and utilization (FAO, 2002, 2006, 2017).

In a recent assessment of food security in the world, the FAO (2017) estimates that in 2016 the number of chronically undernourished people in the world has increased to 815 million, up from 777 million in 2015 although still down from about 900 million in 2000. The food security situation has worsened in parts of sub-Saharan Africa, South-Eastern Asia and Western Asia. Deteriorations have been observed most notably in locations with armed conflict and locations where conflict is combined with natural disasters such as droughts or floods. While food insecurity is measured by a multidimensional set of variables and it is largely observed recently due to armed conflict, and conflict combined with natural disasters, this paper focuses only on the nexus between water and food production.

With increased levels of water scarcity and its supply variability, the ability of Planet Earth to meet the growing demand for food of more people with less available resources per capita becomes a major policy concern. A response to this concern could include the following: develop technologies that would allow crops to grow faster, require less water and fertilizers, and produce higher yields per unit of land; and allow the use of lower quality water, and be grown on lower quality soil (Mann, 2018).

To some, this response might be a utopia. Indeed, looking at some statistical facts (below) from around the world (continents) suggests that water scarcity per capita increases, that arable land per capita declines in most continents, and that future climate change continues to affect water availability in the future. However, despite these odds, total production[1] of major staple crops such as wheat, soybeans, maize, and rice, and the food consumption per capita (measured in Kilocalories per day) continues to steadily increase over time.

While such trends may be impressive, the gap between what is considered a reasonable level of food consumption per capita and the actual level may still not be met under future conditions of population growth, resource scarcity, and climate change. The goal of this paper is to review previous work and using available data to identify constraints to food production due to water availability.

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[1] This could be the result of either increased yield per unit of land or expansion of land growing these crops.

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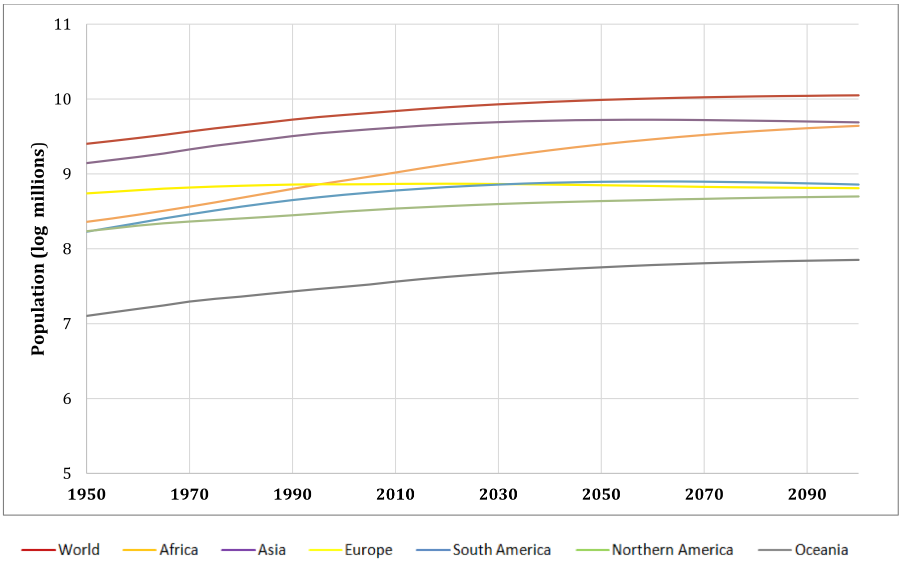

Fig. 1. Population in the world and continents 1950–2100.
Note: Population data for 2016–2100 is based on UN medium growth estimates.
Source: Population data for 1950–2015 is from the United Nation, Department of Economic and Social Affairs, Population Division (2015).

The analysis we perform in this paper highlights the question raised by Malthus (1798) about whether or not the world will be able to feed its population. The basic assumptions in the theory developed by Malthus suggest that world population increases exponentially, and that food production increases arithmetically. Therefore, according to Malthus, the world is moving towards a catastrophic famine. In retrospect, at least the population growth assumption is proven wrong. Nearly one hundred and fifty years later, Boserup (1965) questioned Malthus's theory and suggested that food production can, and will rise to match the population needs, by means of technological change (coined by Boserup: 'agricultural intensification') that will improve farming methods by inventing new technologies. A similar trend was suggested by Hayami and Ruttan (1985), using the term 'induced innovation'. The results of Hayami and Ruttan's meta-analysis further demeans the pessimistic Malthusian view of the natural resource constraint on agricultural production. These theories assume that innovation and technology will meet population needs. They have not considered the overall effects of population growth, fixed or declining arable land and its quality, and water availability and quality. The changing climate may also alter the future distribution of agricultural production in various regions of the world.

We use global data on population growth, water, and land for food production. Food production is examined by climate change, water scarcity impacts, and technological advancements that may ensure a sustainable food supply under water resources constraints. The debate on water scarcity and how to measure it is not new. Recent literature (e.g., Damkjaer and Taylor, 2017; Xu and Wu, 2017) addressing water availability indices, doesn't leave a doubt that there is not a single water scarcity index that serves all purposes. Several water scarcity indices considered in the literature include: (1) The freshwater *Withdrawal-To-Availability* (WTA) ratio defined water scarcity in terms of the ratio or percentage of total annual withdrawals (Raskin et al., 1996) such that the higher the ratio the larger the scarcity; (2) The *Water Stress Index* (WSI) defined as available renewable freshwater per capita in a region, country, continent, or the world (Falkenmark, 1986). We selected to use the WSI because it was originally developed to inform strategies for food self-sufficiency in light of anticipated future droughts and a growing population, the variables that our paper is concerned with as well. Another reason for selecting the WSI is that it became the most widely applied measure of water scarcity in literature (Damkjaer and Taylor, 2017). Finally, WSI allows us to refer to interannual trends in water scarcity, which is supports the analysis in our paper.

In addition, global and regional ratios of inputs such as water and land are used as indicators for food security risk trends in various locations, which can be captured and provide meaningful interpretation to differences in pressure of water and land quantity and quality on food production across space and time (Magelgaard, K., 2012; McLaughlin and Kinzelbach, 2015). As indicated earlier we elected to use water and land availability per capita as they allow us to better express trends over time and across continents.

We start by describing the global data on population growth, water and land availability and food production. We introduce considerations of climate change that could add to the severity of water availability and thus affect food production. We then discuss possible ways to locally increase the supply of irrigation water by using wastewater, harvested water, and flashflood water. Then we introduce technological and agronomical advancements and their possible impact on irrigation water use efficiency (e.g., salinity, drought, insect tolerance).

2. Trends in food availability and its determinants

We perform a simple trend-analysis of several factors associated with availability of land and water resources—major resources associated with food production. Due to significant scale differences between the various continents we present some of the trends using a logarithmic scale of the dependent variable.

2.1. Population growth

One of the most important variables in the equation of available resources is the growth rate of the population in the world and in the various continents. As can be seen in Fig. 1,[2] population grows exponentially (presented in a logarithmic scale) in almost all continents (except Europe), with Africa showing the highest growth rate over this period. Population growth places increased demand on available resources.

We present changes in resource scarcity over time for land and for water in the next section. Land and water are the main resources

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[2] For all continental graphs we use the same legend, unless otherwise indicated.

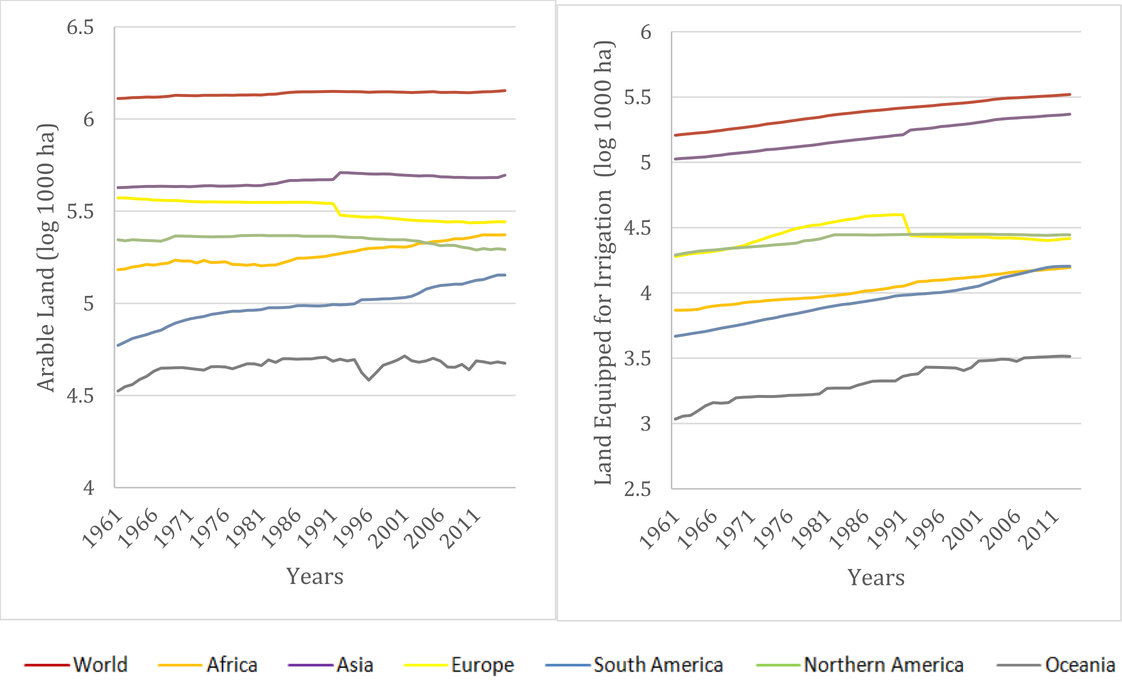

Fig. 2. Total land resources (arable, equipped for irrigation), 1961–2015.
Source: Arable Land data under Land Use domain retrieved from Food and Agricultural Organization (FAO Statistic Database (2015)) .

Table 1
Percent Change of Cropland Area and Land Equipped for Irrigation (1980 vs. 2016).
Source: Cropland and Irrigated Land Equipped data under Land Use domain retrieved from Food and Agricultural Organization ((FAO Statistic Database 2016)).

Regions	Cropland Area 1980 (1000 ha)	Cropland Area 2016 (1000 ha)	Percent Change Cropland Area	Land Equipped for Irrigation 1980 (1000 ha)	Land Equipped for Irrigation 2016 (1000 ha)	Percent Change Land Equipped for Irrigation
China, mainland	99305	134900	35.84	48395	72626	50.07
India	168154	169463	0.78	40835	70400	72.40
Bangladesh	9387	8594	−8.45	1520	5500	261.84
USA	190624	154862.	−18.76	1600	5400	237.50
Iraq	5439	5300	−2.56	1750	3525	101.43
Australia	44186	46378	4.96	1500	2546	69.73
Japan	5461	4471	−18.13	3055	2432	−20.39

needed for food production and are the focus of this paper.

2.2. Trends in land and water availability

We express availability of the resource in terms of annual per capita. To realize the trends in arable (or equipped for irrigation) land per capita and in renewable water resources per capita we divide the total available water and the total arable (or equipped for irrigation) land by the population in each year. Since available land resources (or even decline, due to salinization and other soil quality degradations) and water resources are more or less constant (or even decline due to climate change-droughts and degraded quality) over time, one obtains high hyperbolic trends for both of these important resources—land and water, which are essential for food production. Fig. 2 presents the available arable and equipped-for-irrigation land resources. Table 1 presents changes in irrigated land in selected countries between 1980 and 2016, suggesting increase investment in irrigation.

As suggested by several sources (Desertification Indicator System for Mediterranean Europe, No Date; Siebert et al., 2015), land equipped for irrigation can be fallowed temporarily or permanently due to droughts. This measure (the amount of actual irrigation water used in the area where there is irrigation equipment) shows to what extent irrigation water resources are available, and actually used or (for many reasons) not used. In many areas there is irrigation infrastructure but, due to reduction in water availability (due to drought or competing demands), it is not used for agriculture anymore. In Table 1 we present a list of randomly selected countries faced with such phenomena.

Table 1 suggests that not all land areas equipped for irrigation were functional or implemented for cropland use. In both Bangladesh, USA, Iraq, and Japan the area of cropland is lower despite the increase in the equipped land for irrigation. This may imply that there was not enough water supply for all equipped area in 2016 due to drought, hence, a decrease in crop harvest during that year. Furthermore, in regions such as India and Australia, in order to maintain the same level of cropland area each year, land equipped-for-irrigation has jumped dramatically up to 72% in India, and 69% in Australia. While in Japan, areas equipped for irrigation have decreased by 20%, which may be due to the poor irrigation efficiency on rice cultivation that leads to water loss, or irrigation equipment were shut down due to the increase of drought periods (FAO, 2016). It could also be that more irrigated land is equipped in order to compensate for the reduction in crop land, or that irrigation was considered a more attractive economic investment resulting in the increase in irrigated area between 1980 and 2016.

As can be seen in Fig. 2, arable land is relatively constant while land equipped-for-irrigation increases over time due to investments in irrigation projects. A monotonic increase through time is observed in all continents, except for a drop in irrigated land in Europe in early 1990s followed by a flattened trend afterwards. But these trends change when

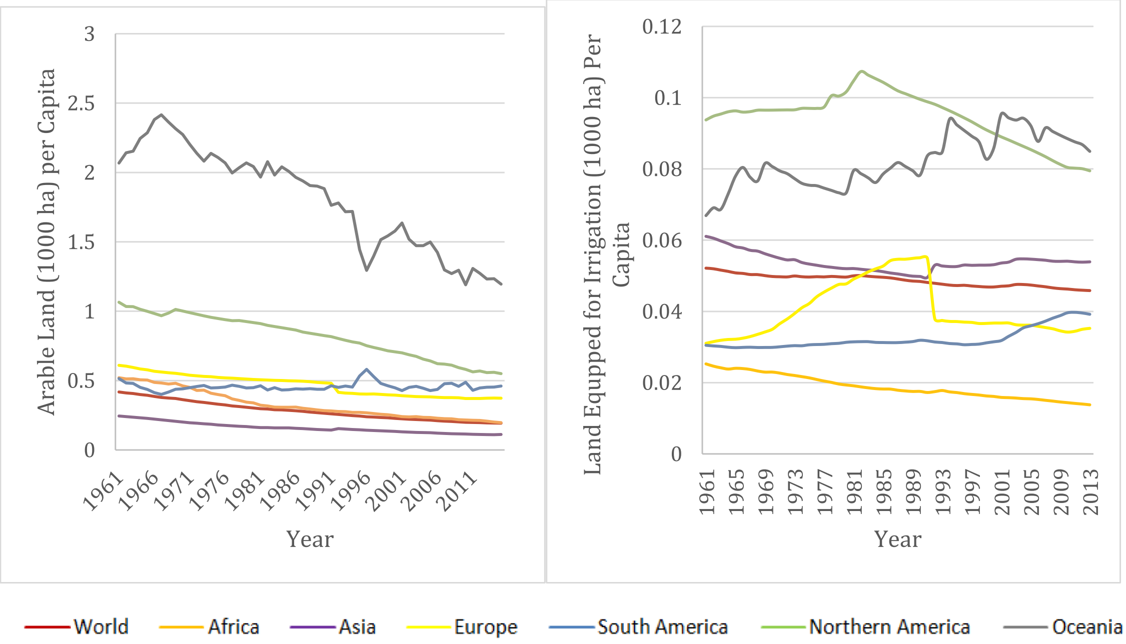

Fig. 3. Total land resources per capita (arable, equipped for irrigation), 1961–2013.
Source: Arable Land (for 2015) and Area Equipped for Irrigation (2013) data under Land Use domain retrieved from Food and Agricultural Organization (FAO) Statistic Database.

we examine (Fig. 3) the per capita values of arable land and land equipped-for-irrigation. Arable land per capita continues to decline each year in almost every continent of the world. Land equipped-for-irrigation per capita declines in some continents (e.g., Africa) and reflect removal of irrigation equipment in certain years because of droughts.

Fig. 3 (left panel) suggests that in most continents the available arable land per capita is fixed, or slightly declines over time, suggesting that new land is reclaimed for agricultural cultivation over time in a pace that exceeds population growth, or that agricultural lands were lost due to urbanization, desertification or desalination. Or possibly, in certain countries/continents (e.g., Europe), population growth is lower and arable land is constant so the decline over time is minute. Only in Oceania and Northern America the decline per capita of arable land is more significant. Fig. 3 (right panel) suggests that land equipped for irrigation per capita increases over time, which is the result of increased investment in irrigation projects in most continents. Only in Africa, the land equipped for irrigation per capita is declining over time.

The land situation is very similar for trends in water resources availability. Fig. 4 below presents total annual available water resources in the various continents between 1960 and 2100.

When dividing the renewable water resources by the population one obtains a fast and crude measure of scarcity: renewable water availability per capita (Falkenmark, 1986, 1989). Fig. 5 presents this index for various water types (surface, GW, and total water resources) for the world and continents for the period 1960–2100. Projected population from the year 2020 and onwards are based on medium variant calculations taken from the UNDP's World Population Prospects: the 2015 Revision. The results should be interpreted as water available for various uses, including, domestic use, irrigation, industrial, and environmental, to name a few. The allocation of these water across uses is a policy decision. When one talks about water availability per capita it is for all uses (food production, residential in-home use, residential outdoor use, energy production, and others). In that respect, Dinar S. et al. (2011) argue that decision makers and analysts in a particular state consider for their policymaking not only the level of water availability per capita at present, but also future trends in water scarcity that are calculated based on population growth predictions and perceived water shortages. It is therefore, the local policies that consider societal preferences and priorities for allocation of available water for food production, residential consumption and environmental usage. Therefore, showing the negative trend of water availability per capita is an important analysis that addresses the time trends rather than the absolute amount of available water.

2.3. Food production trends

Following the definition we used earlier, food security is determined by many factors, including: level of food production, agricultural trade and domestic distribution channels, market institutions for provision of inputs and products, water supply, and climate change, to name a few.

We turn now to present trends of food production over time for main staple crops and for the various continents.

Fig. 6 presents the increase of total major staple crops production throughout the years to show a steady increase in the amount of food gained through time. This can be from either the result of area expansion for these major staple crops or the result of increased yield per unit of land, or both. As seen in Fig. 7, the yield of major staple crops ton per hectares, there is a steady increase as well. Thus, the reasoning behind this can be from either scientific and management advancements, as both total food production and yield of major staple crops ton per hectares have increased.

Note: Due to the difference in yield per ha range, we do not include the trends in sugar-beet in this graph. However, sugar beet global mean-yield per ha in 1961 and 2016 was 50.26 and 70.61 tons, respectively.

Another measure of food production is presented in Fig. 8. As can be seen in Fig. 8, supply of kilocalories per capita in all continents is non-decreasing over the period analyzed, although there is a constant gap between per capita kilocalories between well-fed continents (Europe, Northern America) and mal-fed continents (Africa, Asia), reaching more than 1000 kilocalories per day.

Crops also thrive depending on the agroecosystems. Agroecosystems are agricultural ecosystems that are managed by farmers to produce food, fiber, and other agricultural products. Agroecosystems determine what farming systems are used in order for crops to thrive within their set climate conditions, whether it should be irrigated, rainfed, or both.

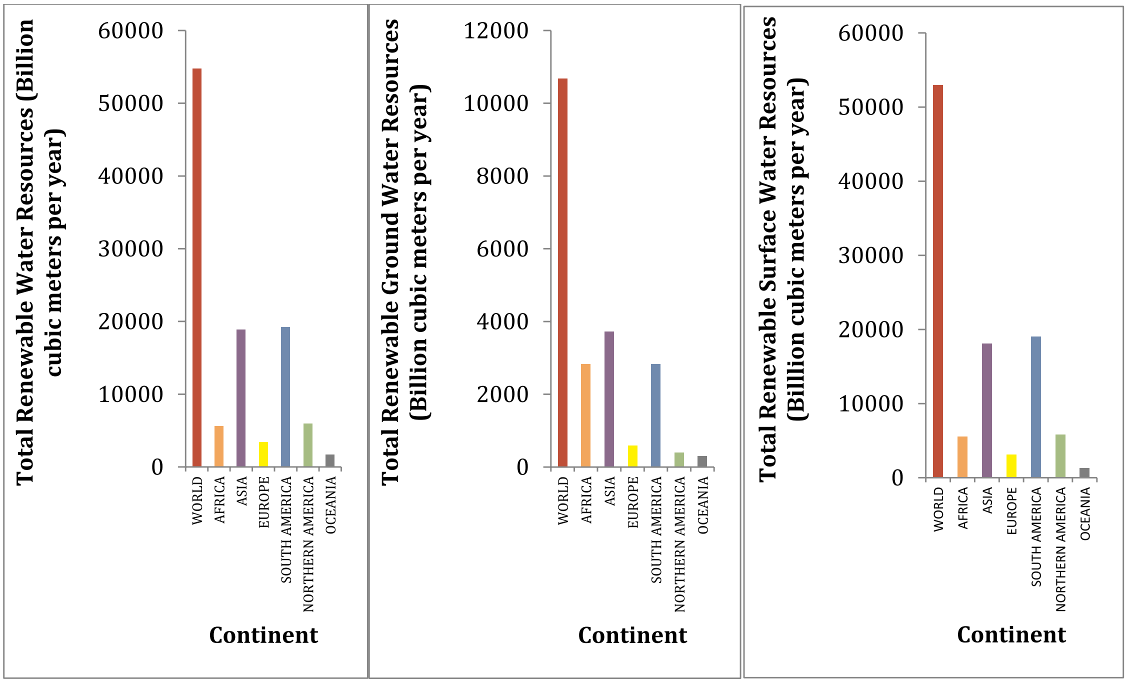

Fig. 4. Actual and projected available renewable water resources in the world and by Continent, 1960) to 2100 (from left to right: Total water, GW, surface water (billion Cubic Meters per year).
Note: While available renewable water resources are constant in the figure, we should be aware of the long-term reduction in their availability due to increased frequency of droughts and due to increased rates of pollution that makes water non-useable.
Source: Water data from FAO AQUASTAT (n.d.).

Table 2 depicts a few examples of agroecosystems and crops for both global and regional areas. Depending on the agrosystem, different crops are grown in different regions to maximize yield (assumption). As seen in the table below, similar agro-ecologies grow similar crops like Mexico and Peru (maize), and Morocco and Turkey (durum wheat). Provided below is a table of examples of different region's agro-systems and the crops grown.

The analysis so far suggests that on the one hand world population is growing exponentially; available land and water resources do not increase; thus available per capita resources do not increase but

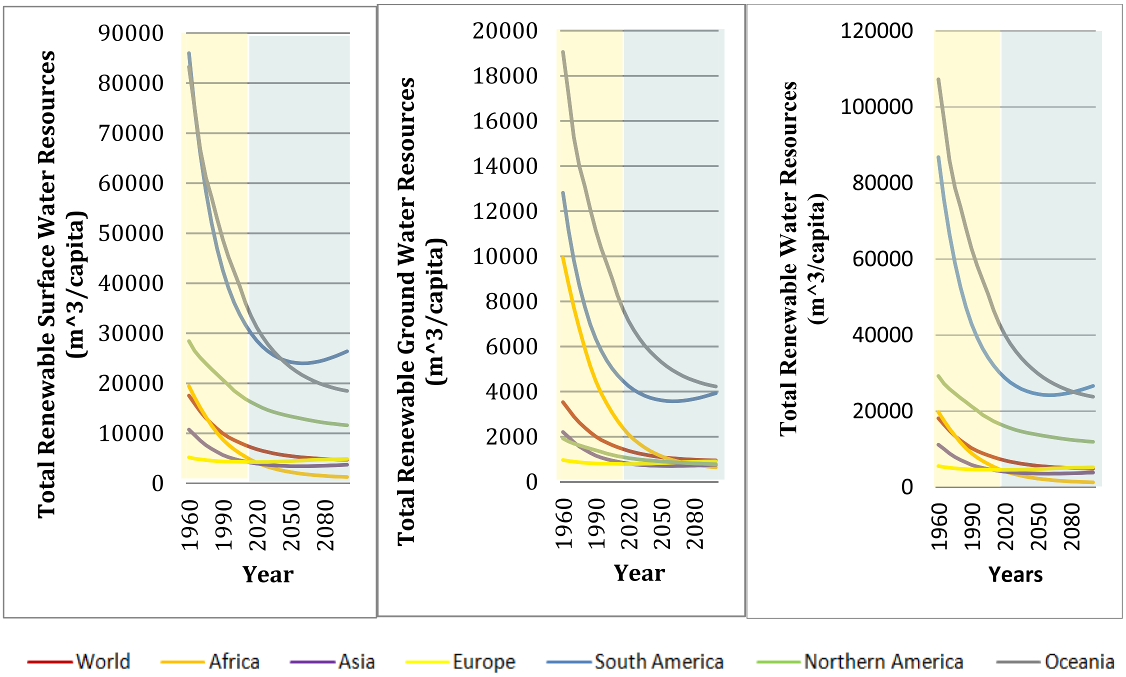

Fig. 5. Estimation and Projection of available renewable water resources per capita in the world and by Continent, 1960) to 2100 (from left to right: Total water, GW, surface water (Cubic Meters per Person per year).
Note: Yellow-highlighted period refers to actual population numbers; Green-highlighted period refers to projected population numbers.
Source: Water data from FAO AQUASTAT (n.d.).

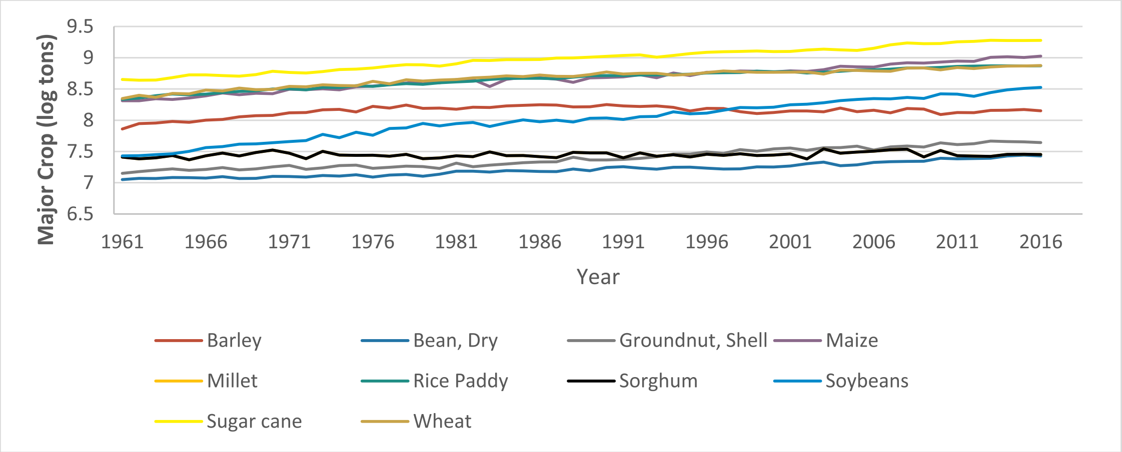

Fig. 6. Production of major staple crops 1961–2016 (Ton).
Source: Crops data retrieved from Food and Agricultural Organization ((FAO Statistical Database 2016)).

decrease overtime. On the other hand, the analysis suggests that total production as well as yield per unit of land of major staple crops increases over time. This is reflected in a positive trajectory of supply of kilocalories per capita in all continents.

Two questions emerge from the trends we have seen: (1) Are these positive trends in food production a result of a technological change that allows to produce more food with less resources, as was suggested by Mann (2018); and (2) will the positive trends in food supply increase per capita be sufficient to cope with global population growth and impacts of climate change? In this paper we focus only on the interaction between water and water-related inputs, and food production.

Before moving on to discuss advancements that increase food productivity per unit of water and per unit of land, we must consider another aspect that threatens food security: climate change. Climate change is expected to affect crop yields both directly and indirectly through water availability. The next section provides some qualitative considerations of climate change and food production.

3. Future impact of climate change on water resources and crop yields

Climate change is expected to further affect water availability in the future in an uneven manner across the various continents around the world, skewing further its already uneven spatial availability. Using different simulations that account for both Representative Concentration Pathways (RSPs) and time horizons, future water availability around the globe is predicted. As can be seen from Fig. 9, run 32 (left panel) and run 39 (right panel) illustrate two Coupled Model Intercomparison Project Phase 5 (CMIP5) models of past and future annual mean precipitation change globally. Run 32 (1986–2005) acts as the baseline for both the pessimistic models of precipitation (Run 39) and runoff (Run 33) caused by climate change in the year 2081–2100.

Some regions are affected in the same way, but in different magnitudes for both runs. Regions with increase of precipitation are connected to the increase in runoff as seen in both Run 39 and Run 33. From the figure, a large reduction in average precipitation and runoff can be seen in certain areas such as Europe, western Asia, and South America, but also a dramatic increase in these factors in countries like Central Africa, Russia, and Australia. Table 3 presents ranges in projected annual mean percent change of precipitation and runoff by continents and subregions. It is clearly seen that there are regions that will be subject to more significant variation in changes to precipitation and runoff, such as Africa and South America.

From Table 3, some regions that have started off with less precipitation are predicted to increase in the future due to climate change. For instance, as of 1986–2005, Indonesia had a percent change in precipitation of about −10 to 10% but this is expected to increase from up to 0–20% more in precipitation in the future. However, the situation could be the opposite, such as for the northern part of South America it is predicted to continue its strain on precipitation as it goes from −20%

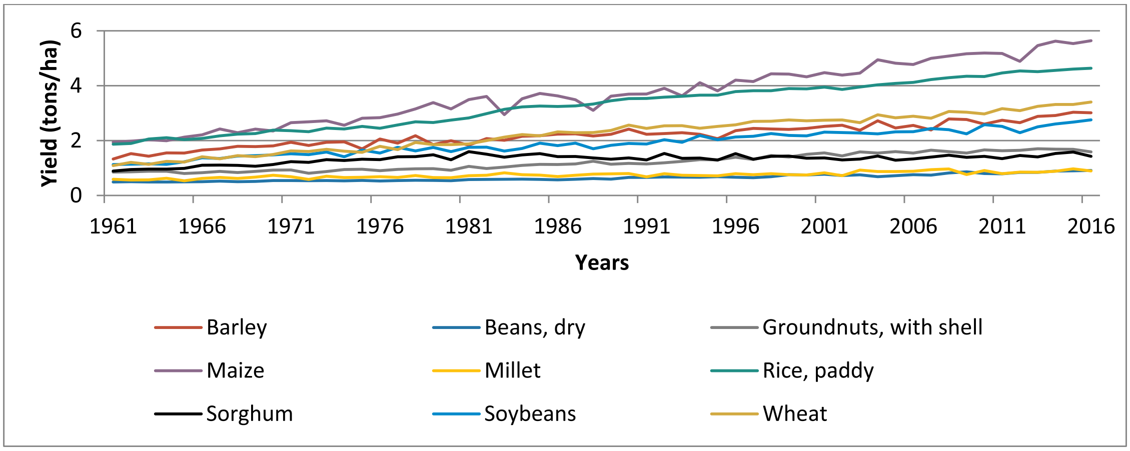

Fig. 7. Production of food from major staple crops (Ton/Ha) 1961–2016.
Source: Crops data retrieved from Food and Agricultural Organization ((FAO Statistical Database 2016)).

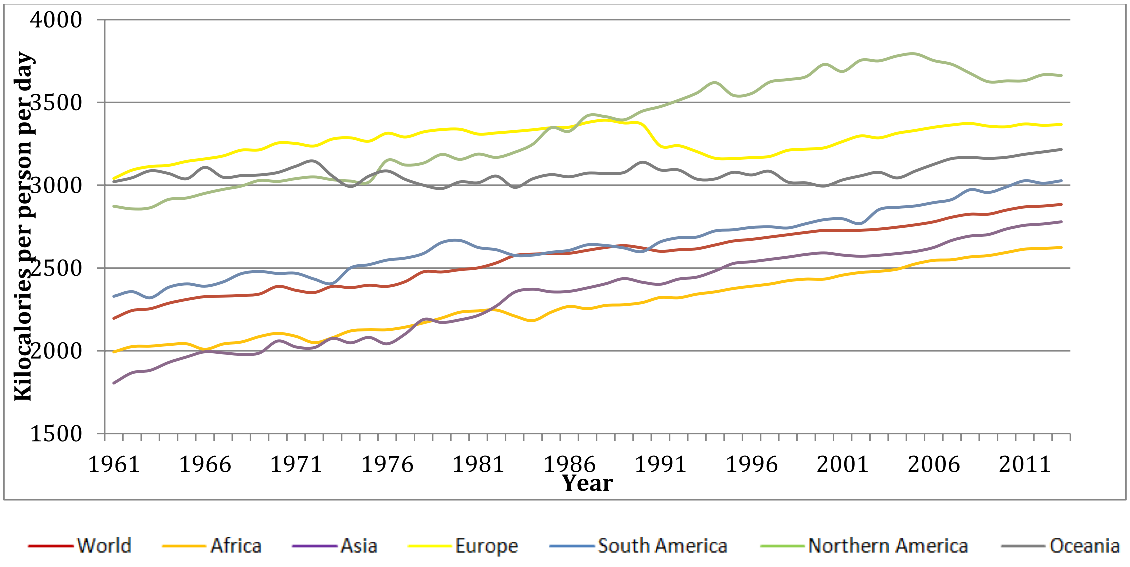

Fig. 8. Production of Food (Kilocalories) per capita by continents 1961–2016.
Source: Daily kilocalories supply data under Food Balance Sheets domain retrieved from Food and Agricultural Organization (FAO), 2016.

Table 2
Global & country agro-systems & crops.
Source: Regions of Agroecosystem information provided by De Boef, W. (2000) and Jarvis, D. & Rao, R.V. (2002).

Country/ Global	Farming System	Agro-ecology	Crops
Global		Countries in all five regions (Americas, APO, CWANA, Europe, SSA)	24 different crops: selting outcrossing, clonal including crops from Gef Ethiopia, Mali/Zimb (Banana/ Plantain) (Yam/ domestication)
Mexico	Shifting cultivation	Tropical lowland shifting cultivation	Mazie Beans Squash Chilli peppers
Peru	Shifting cultivation	Tropical lowland shifting cultivation	Cassava Groundnut Maize Chili peppers
Nepal	Irrigated and rainfed	Mountain, mid-hills and lowland irrigated and rainfed	Rice Barely Finger Millet Taro Sponge Gourd Pigeon Pea
Vietnam	Irrigated and rainfed, upland agriculture	Tropical lowland, medium elevation Irrigated and rainfed	Rice Mung Beans Taro
Hungary	rainfed	Temperate	Maize Beans
Burkina Faso	rainfed	Arid and semi-arid	Sorghum Cowpea Millet Okra Fra fra potato
Ethiopia	Rainfed dry land	Tropical highland	Sorghum
Morocco	Irrigated and rainfed and oasis system	Tropical highland	Durum wheat Barley Alfalfa Faba bean
Turkey	Irrigated and rainfed	Transition zone	Durum wheat Chickpea

to −30% of precipitation and −40 to 0% change in runoff. It is not surprising to realize from Fig. 9 and Table 3, that regions prone to reduced precipitation and runoff are regions with high temperatures and characterized by the highest share of water withdrawn for irrigation, as a fraction of total water withdrawals (for irrigation, municipal and industrial consumption). In general, although difference in variation can be observed within sub-regions, the general trend is an increase in precipitation variation between 1986-2005 and 2081–2100 in all continents.

The state of California is an example of a highly productive agricultural sector that is threatened by climate change. In a recent study of Pathak et al. (2018), they provide sufficient evidence that the climate in California has changed and will continue to change in the future. Their findings suggest climate change in terms of temperature, precipitation, snowpack, heat waves, drought and flood will affect the water availability, chill hours, pests and diseases, of 400 different crops in California which all together affect crop yields. The authors suggest a steady decline in yield of staple crops between the years 2010–2090 of about 5–10% (Maize), 2–10% (Rice), 8–15 (Wheat), and 10–25 (Sunflower) [where the more severe decline refers to the B1 Lower Emission Scenario and the lighter decline refers to the A2 Higher Emission Scenario].

Future climate change will have different adverse effects on crop yields in various regions/continents around the world due to areas facing reduced precipitation (Fig. 9), increased temperatures (Fig. 10), and the fact that water withdrawals for irrigated agriculture is the largest in those regions most affected by climate change (Fig. 11). Northern regions such as Canada or northern Europe may face up to 100 percent increase in crop yield, while southern regions are expected to face up to 50 percent reduction in crop yields, as suggested in Fig. 12.

Climate change is expected to affect crop productivity in various ways (Zilberman et al., 2018). In this article we will focus mainly on water-related effects such as redistribution of precipitation, rising sea level and flooding; prolonged and frequent droughts, to name a few. Some of these effects lead to secondary impacts such as increase pest activity due to rising temperatures and weakening of crop resistance. Lack of sufficient amount of irrigation water could potentially lead to a reduction in yield as well as it affects the salt leaching processes and lead to increased salinity in the soil, affecting further crop yield. These effects together lead to weakening of the ability of the plants to resist

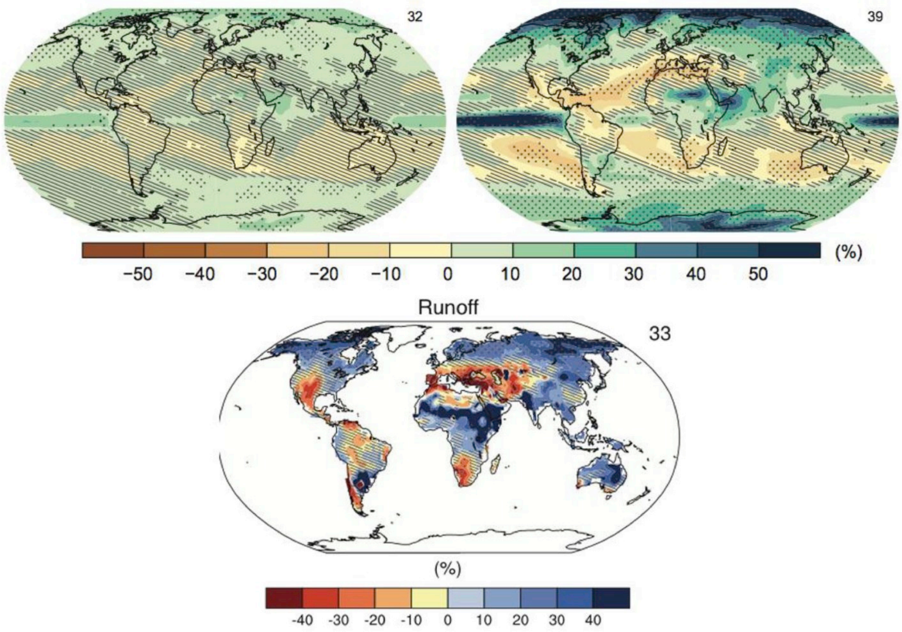

Fig. 9. Percent change in average precipitation 1986–2005 (left, baseline period) to 2081–2100 (right, Projection period) & projected percent change in average runoff 2081–2100.

Note: No baseline for runoff is provided. The 2081–2100 results are relative to 1986–2005 as in run 32.

Source: U.S. Environmental Protection Agency (2016) & IPCC, 2013.

pest and disease effects, thus resulting in further yield reduction (see section of pest and disease tolerant crops). Extremely high amounts of water, due to flooding, can also be harmful to crops by reducing or terminating a crop's aeration. These are just several examples, to the effect of climate change and irregularity in the supply of water (droughts, floods) with direct and indirect impact of food production.

A handful of publications addressed the likely impact of climate change on food security, by focusing on quantifying such impacts. Turral et al. (2008) estimate the various dimensions of climate change impact on food security and means of adaptation. In addition to quantifying likely reduction in yields and increase in food insecurity, the authors also identify prospects for adaptation to climate change at various levels as is detailed in Table 4 below.

A similar categorization as in the table, in Giordano et al. (2017) includes recommendations to (1) increase yield per unit of water consumed, (2) to reduce non-beneficial depletion of water, and (3) to tap uncommitted water flows.

We report a few of the numerous studies that attempted to estimate impact of climate change on food security. Schmidhuber and Tubiello (2007) for example, review literature that aims at quantifying the

Table 3
Ranges in projected annual mean percent change of precipitation and runoff by continents and subregions (2081–2100).
Source: IPCC, 2013.

Continents/Regions	Precipitation Range 1986 to 2005 (% Change)	Precipitation Range 2081 to 2100 (% Change)	Runoff Range (% Change)	Variation & Comment on Projected 2081 to 2100
Asia	−10 to 30	−30 to 50	−50 to 50	Highly Varied, Majority in 0–40% range
Central & Western Asia	−10 to 20	−30 to 50	−50 to 0	
Eastern Asia	0 to 10	0 to 30	−10 to 50	
Northern Asia	0 to 20	0 to 50	0 to 50	
Southern Asia	0 to 10	10 to 30	0 to 50	
Africa	**−30 to 20**	**−30 to 60**	**−50 to 50**	**Highly Varied**
North Central Africa	−30 to −20, 0 to 20	0 to 60	0 to 50	
Northern & Southern Africa	−20 to 20, -30 to 0	−30 to 0	−50 to 0	
Europe	**−20 to -10, 0 to 10**	**−30 to 30**	**−50 to 30**	**Moderately Varied**
Northern Europe	0 to 10	0 to 30	10 to 30	
Southern Europe	−20 to −10, 0 to 10	−30 to 0	−40 to 0	
South America	**−20 to -10, 0 to 10**	**−30 to 30**	**−50 to 50**	**Moderately Varied**
Northern & Southern most South America	−20 to −10, 0 to 10	−30 to 10	−40 to 20	
Southern South America	0 to 10	0 to 20	10 to 50, -50 to −40	
North West & Central South America	−20 to −10	0 to 30	−20 to 0, 0 to 50	
North America	**−20 to -10, 0 to 10**	**−30 to 60**	**−40 to 50**	**Highly varied**
Central & Southern North America	−20 to −10, 0 to 10	−30 to 0	−40 to 0	
Northern North America	0 to 10	0 to 50	0 to 50	
Oceania	**−10 to 10**	**−10 to 20**	**−40 to 40**	**Moderately varied, majority in range 10 to 30% & within -0.2 to 0**
Indonesia	−10 to 10	0 to 20	10 to 30	
Northern Australia	−10 to 0	10 to 20	10 to 50	
Southern Australia	−10 to 0	−20 to 0	−40 to 0	

Note: Values are rough estimates, based on a delineation of the maps in Fig. 9.

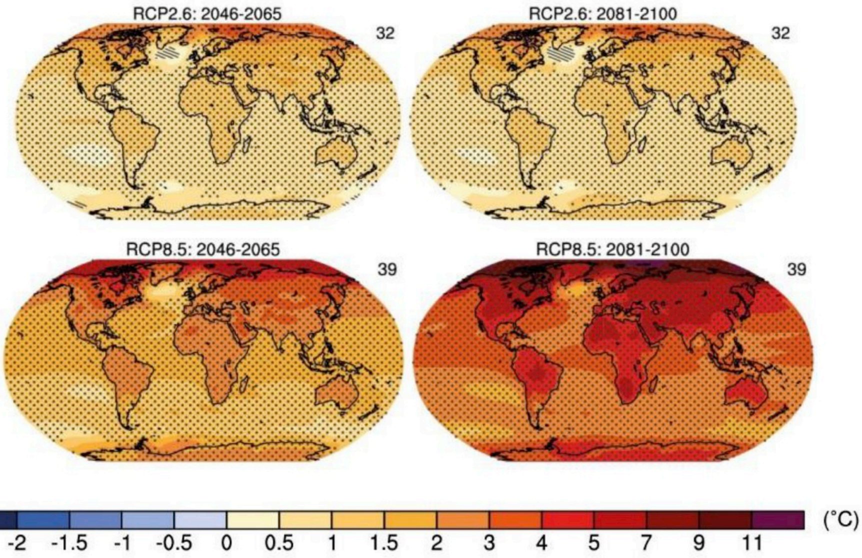

Fig. 10. Annual mean surface air temperature change (%) between 2046-2065 and 2081–2100.
Source: U.S. Environmental Protection Agency (2016).

impact of climate change on all four components of food security—production and availability, supplies, utilization, and access. These authors also accounted for the positive effect of increased CO2 concentration. They find that so far, published results indicate that the impacts of climate change via water and temperature are significant, however, with a wide projected range (between 5 million and 170 million additional people affected by hunger by 2080) which is strongly dependent on assumed socio-economic development. However, with the dynamic movement of agro-ecological zones due to climate change, the estimations of global effects due to temperature and precipitation change are more difficult to calculate.

Another review by Wheeler and von Braun (2013) recognize the limitations of global circulation models in predicting future precipitation due to climate change and suggests that due to the inability of the current models to represent the global hydrological cycle accurately the changes in rainfall patterns, particularly over tropical land, are less certain. The authors expected that the summer Asian monsoon rainfall will intensify, while areas in north and southern Africa will get drier. Both these trends, of course, will have a negative impact on food production and food security, as argued in Rosegrant et al. (2009) there is an existence of uncertainty in the prediction that increase (decrease) in precipitation is expected mainly in high (subtropical and lower) latitudes. Similarly, it can be anticipated that access to food and its utilization will also be affected indirectly via collateral impacts on household and individual incomes, and by loss of access to drinking water and health deterioration.

Hanjra and Qureshi (2010) identify a nexus of interactive forces that all together challenge food security under climate change. These forces include climate change, water scarcity, energy crisis, and credit crisis. In order to address food security under water scarcity and climate change, there needs to be an improvement in water efficiency by moving to a more energy-driven irrigation system, which would be high in energy and investments. Therefore, any approach undertaken to address food security would need to account for all 4 forces.

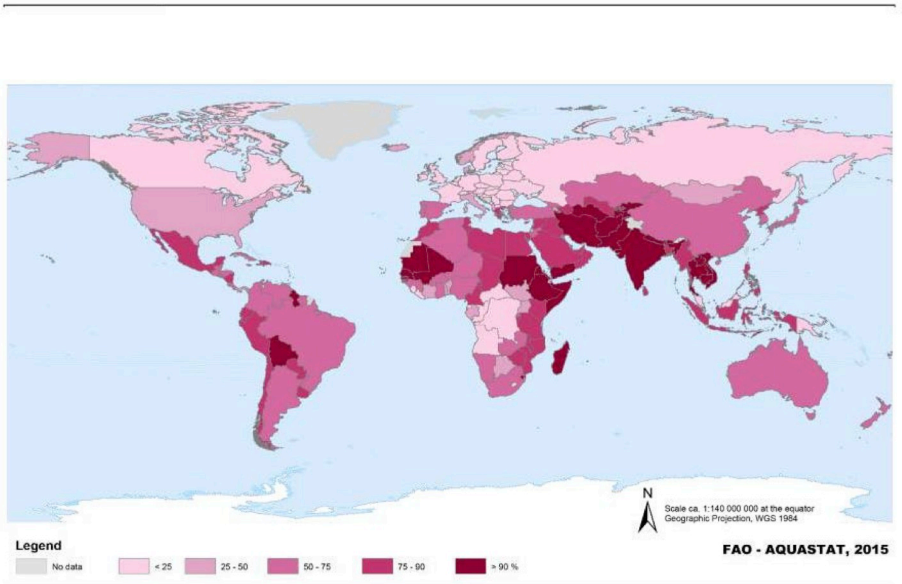

Fig. 11. Agricultural water withdrawals as a share of total withdrawals (for irrigation, domestic, and industrial consumption).
Source: FAO AQUASTAT (2015).

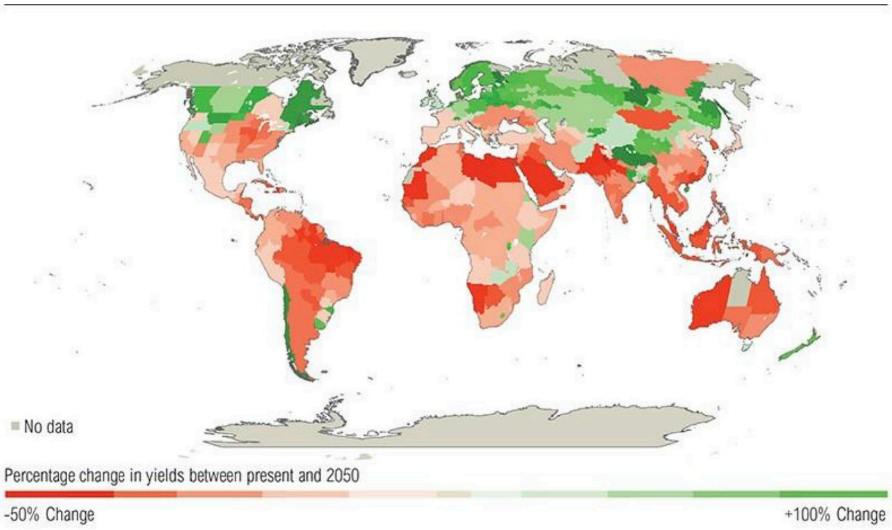

Fig. 12. Projection of percentage changes in crop yields due to climate change impacts by 2050.
Source: World Resources Institute (n.d.).

Table 4
Prospects for adaptation to climate change in the agricultural food production sector.
Source: Adapted from Turral et al. (2008).

	Major adaptation strategies	
Adaptation on Farm	Crop selection and crop growing calendar	(1) Adoption of enhanced crop varieties; (2) Improved water productivity; (3) Introduction of agroforestry systems, (4) Diversification of high-value crop production; (5)
	Fertilizer management	
	Water management on farm	(1) Enhancing rootzone moisture storage, (2) Reducing unproductive evaporation, (3) Improving irrigation management and flexibility on farm
	Irrigation technologies on farms	
	Depletion accounting	
	Flood protection and erosion	
	Commercial agriculture	
Adaptation at irrigation system level	Water allocation	
	System performance	
	Cropping patterns and calendars	
	Conjunctive use of surface water and groundwater	
	Irrigation policy measures	
Adaptation at river basin and national levels	Irrigation sector policy	
	Coping with drought	
	Coping with flooding	
	Managing aquifer recharge	

Several publications reviewed models that assess either water security, food security, or both (McNeill et al., 2017 and the literature they cite). The most relevant review in McNeill et al. (2017) is that of ten models that address food and water security (global and regional models). The main features in most models include: irrigation water requirement, hydro climatic variables, water management practices, and crop production functions. The objective in McNeill et al. (2017) was to identify limitations of the models in addressing physical shocks to the food and water system.

We focus in this section on policies and technological advancements that may alleviate water scarcity and its impact on food production. We review useful suggestions to address water scarcity and climate change impacts on food production through three lines of interventions: (1) Increasing water supply, (2) Introducing institutional arrangements to better manage the available and disrupted water supply, and (3) Introducing technologies, including genetic developments.

4. Reviews of possible solutions to addressing the challenges

Several alternative ways to address the challenge of food production under reduced water availability include supply side approaches, demand side approaches, institutional and technological approaches, and scientific solutions to adapt to climate change and lower water availability.

4.1. *Increasing the water supply side*

Several water experts argue that while water resources grow in scarcity, there are still existing approaches that allow sufficient supply of water for irrigation. Among the practices mentioned in the literature are (1) water harvesting, which refers mainly to capturing and storing rainwater for reuse on-site, rather than allowing it to run off (Yuan et al., 2003; Liang and van Dijk, 2011); (2) reuse of treated wastewater for irrigation and other purposes, which has been found to be feasible and is wide spread in several countries such as Tunisia, Israel, Australia, to name a few (Hernandez-Sancho et al., 2015; Hussain et al., 2001; Winpenny et al., 2010); and (3) managed aquifer recharge, which uses water in abundant years to recharge groundwater aquifers for use in scarce years (Karimov et al., 2013; Maliva, 2014).

All three approaches to increase water supply are technically feasible and have been attempted at various locations around the world. However, each of them needs a support in the formation of a strong institutional system, which might not function well.

4.2. Introducing institutional innovations

Water management under scarcity could be enhanced with appropriate institutions that support the implementation of technological solutions. Scheierling and Treguer (2016) identifies there are limitation of technical water supply options as water scarcity grows, thus suggesting to invest in policy and institutional measures instead. The authors identify the advantages in measures that facilitate water reallocation (such as pricing, water trade) and promote and support private adaptation (such as management of groundwater, reuse of wastewater). Yet in a recent work, Scheierling and Tréguer (2018) challenge the objective of what they define as “more crop per drop” approach that leads to major public and private investments aimed to increase water productivity and efficiency in agriculture in both developed and developing countries. The authors distinguish between an irrigated agricultural sector in an expansionary and in a mature phase of the water economy, arguing that different objectives and policy interventions are needed for each.

Trade of water (entitlements sale or short-term leases) among users has long been suggested as one measure to increase water efficiency and sustain agricultural production (Easter and Huang, 2014; Wang et al., 2016). The market institution requires allocation of property rights for water to allow trade. This pre-requisite introduces difficulties in some countries but works quite efficiently in another.

Institutions to promote (incentivize) joint management of water resources, especially those considered common pool resources (such as groundwater), were also practiced in various countries with reasonable level of success. Joint management of common pool water resources was found to sustain the resource, reduce the level of conflict among the users of the resource, and increase agricultural production and the welfare of the communities (Ostrom, 2010; Madani and Dinar, 2012).

4.3. Improvements in irrigation efficiency

Efficiency of irrigation water has been for long time a subject for interdisciplinary discourse. Irrigation water efficiency can be measured at various scales from field to river basin scales, and with various parameters such as yield per unit of water, value of production per unit of water, or actually used by crops vs. water applied, to name a few (e.g., Shyam et al., 2013; Scheierling and Treguer, 2016, 2018; Ward and Pulido-Valazquez, 2008). Irrigation practices show a decrease in water consumption in various regions. As of 2010, the world's mean irrigation efficiently (measured as the ratio between the actual water used by crops and the amount applied) was approximately 56% (FAO, 2014). Irrigation efficiency varies by regions (evaporation rates), crops (water requirements), soil type (water holding capacity), and irrigation technology and management practices (application uniformity).

Although irrigation has helped many countries minimize the expansion of their irrigated land, irrigation systems are not performing to their full potential, but can be improved. As we already discussed, yields can be improved by introduction of new varieties based on better capable R&D for coping with adverse conditions. However, yields can also be enhanced by closing the ‘yield gap’– the difference between the potential yield (identified in experiment stations) a given agro-ecological and climatic zone and the actual yields obtained by farmers in those zones. These yield gaps are the result of, in many cases, failure of the input provision system to deliver inputs at the right time and quantity to the farmers.

Many developed countries already have a large enough irrigated agriculture and small yield gaps, but these yield gaps continue to persistent. However, if regions like Africa and Eastern Europe can reduce or close the yield gaps of major staple crops, experts predict that this can potentially result in feeding another 2 billion people. These actions of course, requires the advancement of agricultural technologies and improving the expansion in irrigated land (Acevedo, 2018).

4.4. Role of technologies and technological changes

The impacts of the 1960s green revolution are still fresh in our minds (Pingali, 2012). Is another green revolution needed for food production to keep up with demand, or that the existing improvements in crop production so far will suffice? We focus in this section on advancements in crop production that may explain the positive trajectory in crop yield per hectare during the past fifty years, despite the increase in scarcity of land and water resources. Agronomic advancements in crop production could be categorized into two groups: genetic and managerial. We will review efforts made in modifying crops to allow better performance under harsh climate, soil and water conditions.

4.4.1. Genetically modified crops

We will mostly be discussing about genetically modified crops (GMO) in this part of the section. Compared to other technological advances, genetic modification of crops are perceived to be faster and more precise because it can introduce new genes that do not occur naturally to an organism in order to give them a strong trait to survive the ongoing climate change. Unlike its counterpart, genetic selection which is slow and imprecise because they can only crossbred traits that they already naturally have which take years cultivate. Furthermore, genetic selection and hybrid often produce sterile seeds that cannot be recycled for use (Loucas, 2017). Therefore, GMOs will be the main focus in this section.

GMOs were created in order to withstand extreme weather conditions, and impacts of pests and diseases, in order to conserve more water, increase water productivity, and be able to meet food demand. GMOs include commercial crops such as herbicide glyphosate resistant soybean or viral disease resistant potatoes (FAO, 2012). Through the years, GMOs has helped improve yields and water/feed efficiency of crops and livestock. In addition, GMOs could also help reduce hunger by improving food quality and influence economic factors for farmers in terms of accessing food (Qaim and Kouser, 2013). For instance, GMOs has increased farmers’ income by an additional 186.1 billion U.S. dollars (Brookes and Barfoot, 2018). Fig. 13 presents countries that have economically benefited by GM crops.

Between 1996 and 2015, crop genetics are responsible for incremental production of 180.3 million tons of soybeans, 357.7 million tons of corn, 25.2 million tons of cotton lint, and 10.6 million tons of canola worldwide (ISAAA, 2016). GM soybeans are the largest GM crop cultivated currently, as 50% of 91.4 million ha of soybean-grown areas were classified as genetically modified. Fig. 14 depicts the increase in global land area for major GM crops between 1996 and 2016 (ISAAA, 2016). The implementation of GM techniques can potentially help crops thrive in lands or weather that are not ideal in order to meet land area

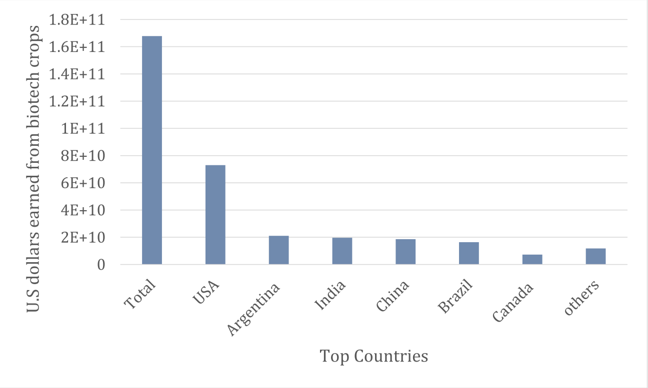

Fig. 13. Economic Benefits of Biotech/GM crops.
Source: ISAAA (2016).

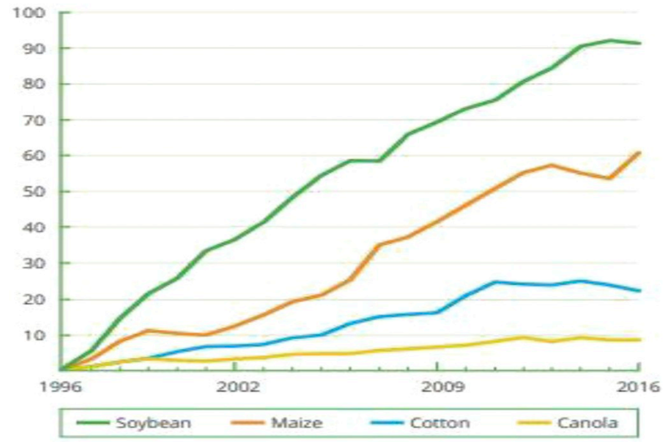

Fig. 14. Increase in global land area for major GM crops between 1996 and 2016 (%).
Source: ISAAA (2016).

demand for agriculture. GM crops can have a larger effect on food availability if most of the crops were commercialized, but due to the lack of public acceptance of GMOs, this prevents further adoption of GM crops (Qaim and Kouser, 2013).

4.4.2. Drought resistant crops

A drought is the condition when precipitation in an area is less than normal. Less precipitation means a decrease in water supply and crop yield due to water deficiency. At least 70% potential yield of crops are lost due to drought and water scarcity (ISAAA, 2008). For instance, due to droughts, on average, there is a 15% loss of maize crop annually and white soybean, one of the most drought sensitive plants, a drought can reduce its yield by approximately 40%. Today, droughts are the leading threat to food security according to the FAO (Liang, 2016). Hence, drought resistant crops (DRCs) were developed to conserve more water and increase crop yield and support food security.

DroughtGard (DG), is an example of an hybrid trait that was developed to maximize crop yield potential under drought conditions. The DG hybrid gene, cspB (cold shock protein) helps in the production of proteins essential for plant growth and stabilizing RNA even when water is scarce (Griffiths and Paul, 2017). DG has shown to increase crop yield by 1.5–2% each year and as shown in the figure below (Fig. 15), areas for DG has steadily increased since 2013 to 2015 within the U.S. (UCSUSA, 2012). Although DGs were originally made for corn, it can also be applied to soybean, cotton, and other specialty crop. DG can only reduce crop yield loss at modest level under drought, but the crop is still a step forward in the advancement of more drought resistant research.

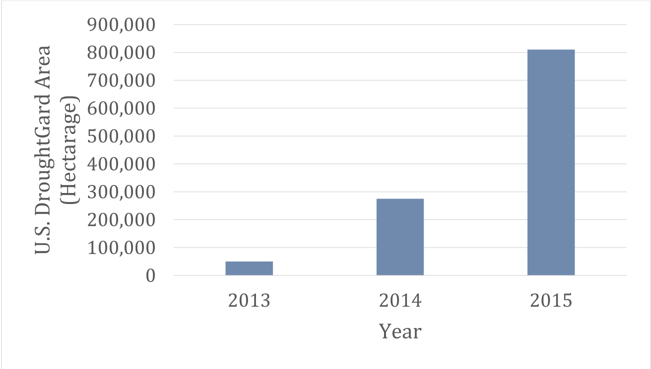

Fig. 15. Area of *DroughtGard* (Ha) in the USA 2013–2015.
Source ISAAA (2015).

Table 5
Performance of drought resistant corn to various water stress levels.
Source: Adee et al. (2016).

Hybrid type	High ET (Tribune site year 2013)	Medium ET (Scandia site year 2012)	Low ET (Scandia site year 2013)
DT	17.2	23.9	32.1
Non-DT	16.4	22.2	32.1
DT WUE Advantage	0.82	1.77	0.05
P > F	0.01	< 0.0001	0.66

Note: Only variables with significant results are presented. Seeding rate, irrigation regime, and interactions were not significant.

As can be seen in Table 5, drought resistant (DR) corn perform differently under different levels of water stress (Adee et al., 2016).

The values in the table compare the Water Use Efficiency (WUE) of Drought Tolerant (DT) and Non-Drought Tolerant (Non-DT) corn varieties. DT corn have a higher WUE in a higher evapotranspiration state while showing similar results to Non-DT varieties at a lower evapotranspiration state. Thus, confirming that in environmentally stressed situation drought tolerant varieties can outperform non-drought tolerant varieties.

Scientists have also developed a form of photosynthesis called CAM (crassulacean acid metabolism) which separates carbon dioxide intake and water outtake from plants. This method helps increase drought tolerance by closing the pores of the plant during the day and opening them during the night; therefore, decreasing evapotranspiration and preventing water from being lost at a faster rate. Pores opening during the night also allows the plant to take in carbon dioxide as storage to create organic acids such as carboxylic acid to initiate the Calvin cycle which allows CAM photosynthesis to occur. CAM photosynthesis can be incorporated into rice, wheat, soybeans, and etc., to reduce the amount of water consumed (Yang et al., 2017). The CAM method will be useful in regions with growing conditions of moderate to severe drought conditions.

4.4.3. Flood resistant crops

Too little water can be a problem, but too much water can be as well. Flooding of agricultural fields can lead to a large loss in the percentage of crop yield. For example, in 2018, a province in China, Sichun was hit with heavy floods that affected 36,900 ha of their crop causing devastating economic loss (Reliefweb, 2018). However, this is known to be common in Asia and Africa as they are often flood prone. Thus, flood resistant crops are needed to prevent huge crop losses. A flood-tolerant rice variety—Swarna-Sub1—was genetically developed in the International Rice Research Institute in Manila, the Philippines, and other collaborating institutions. Swarna-Sub1 can tolerate 14–17 days of water stagnation during floods (with no yield reduction without flooding—Dar et al., 2013) by having a better response to low oxygen levels, morphological and anatomical adaptations, and ethylene regulation of adaptive growth due to flooding (Bailey-Serres et al., 2012). Using a natural experiment of flooding events in 128 villages in India during the 2011 monsoon period, Dar et al. (2013) estimated that the Swarna-Sub1 rice variety provided a 45% increase in yield, and reduced yield variability over the popular variety (Swarna) under conditions of floods that submerged fields for 17 days (Fig. 16).

4.4.4. Other direct and indirect water-related GM traits

While the GM drought and flood resistant varieties are the most direct intervention in crop tolerance of water scarcity, there are additional characteristics where GM varieties can show significant improved performances under conditions of stress from insects, diseases, and water scarcity. Lack of precipitation, long periods of droughts, and additional water stress factors result in weakening crops, becoming more vulnerable and susceptible to insects and disease (CFSPH, 2010).

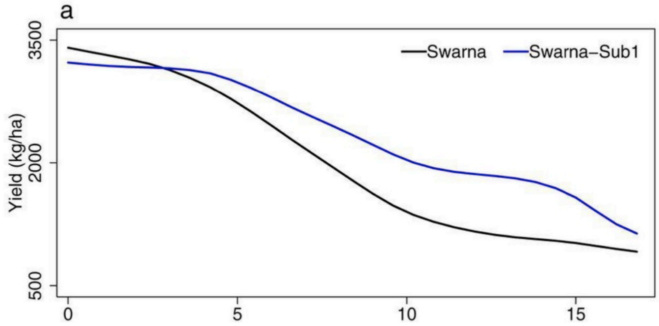

Fig. 16. Impact of Flood-tolerant rice (Swarna-Sub1) on yield during the 2011 monsoon season in India (x-axis = flood duration days).
Source: Dar et al., (2013).

We will not expand on insect and disease resistant varieties but provide just few references to explain the impact of these genetics on food security.

4.4.5. *Weed control*

GM HT technology has led to cost savings and yield increase. The average yield impact across the total area planted between 1996 and 2016 has been 14% and 15% for maize and cotton, respectively. The primary objective of the GM HT technology was to provide more cost effective and simpler weed control, still higher yields were obtained as well. Additional production advancement from this technology has been by enabling of no tillage production systems, shortening the production cycle and thus leading to water savings (Brookes and Barfoot, 2018).

4.4.6. *Insect resistant crops*

A notable cotton IR the Bacillus thuringiensis (Bt) is widely used in developing countries such as India and China to prevent pests like cotton bollworms from damaging crops. Qaim and Kouser (2013) studied the difference in calorie intakes between Indian adopters and non-adopters of Bt. The households who implemented Bt showed a significant increase in their calorie intake, which suggests that the income gained by this adoption has improved their access and security to food. Other works on value of insect resistant crops in Australia addressed crops such as wheat, barley, oats, and grain sorghum (Murray et al., 2013; Crawford and Ordish, 2017), and in several other countries around the world (Brookes and Barfoot, 2018).

4.4.7. *Disease resistant crops*

Annually, 13 percent of global crop yield is lost due to disease (Nelson et al., 2018). Disease resistant crops provide the plants the ability to recognize pathogens and increase levels of resistance and defenses through innate immunity (Nelson et al., 2018). Asian soybean rust (ASR) is a fatal, fungal disease in soybeans which are heavily infected in areas such as Brazil, the second largest producer of soybeans worldwide. It is estimated that 40 to 80 percent of crop yield were destroyed and additional 2 billion dollars per year was lost overall due to ASR alone (Kawashima et al., 2016).

However, fungicide can no longer be as heavily relied on because of the emergence of fungicide resistant diseases. Therefore, to fight against soybean rust, caused by a Phakopsora pachyrhizi fungi, scientists discovered the Cajanus cajan gene. The Cajanus cajan resistance is found within a pigeonpea crops, which are close relatives to the soybeans; hence capable for gene transfer. Thus, if the pigeonpea resistant gene is successfully transferred to soybean it will be able to enhance its tolerance to the phakopsora pachyrhizi fungi and prevent the crop yield loss to ASR (Kawashima et al., 2016).

5. Summary and implications

World population is increasing and water resources per capita is decreasing. Many are indeed concerned about food security at present and in the future. We documented in this paper the trajectory of population growth and water availability per capita in the various continents of the world. Despite increased water scarcity, we were able realize that food production continues to increase per unit of cultivated land and in total. This is probably due to the various technical advancements that were introduced into the agricultural production process.

Preventing crop yield losses due to diseases, floods, droughts, and pests is essential for global food security. A major concern that still needs to be addressed is whether technological advances in genetic engineering or breed and management practices can maintain global food security. The answer to that question is still unclear, especially with climate change continuing to affect water availability, land productivity, and diseases and pests, which in turn, impacts the food production process.

Policy implementation must be addressed as well. Many policies that attempt to keep food production within levels are expensive, long-term, and complicated to implement. Often such attempts tend to be microclimate or soil-specific, so it cannot be generally applied to an entire region or country. Enforcing solutions to each specific micro-climate is difficult. Solutions to global food security does not mean the problem is solved but rather some aspects are slowly improving as more issues continue to appear (as climate change is a never-ending phenomenon). This, however, doesn't mean that the solutions for global food security are not helpful, but that it takes more time and effort to slowly improve the situation.Acknowledgement:

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Conflicts of interest

The authors declare no conflict of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gfs.2019.07.007.

References

Acevedo, M.F., 2018. Food security and the environment: interdisciplinary research to increase productivity while exercising environmental conservation. Glob. Food Secur. 16, 127–132. Accessed April 18, 2018. http://www.fao.org/docrep/015/i2490e/i2490e00.htm.
Adee, E., Roozeboom, K., Balboa, G.R., Schlegel, A., Ciampitti, I.A., 2016. Drought-tolerant corn hybrids yield more in drought-stressed environments with No penalty in non-stressed environments. Front. Plant Sci. 7, 1534.
Bailey-Serres, J., Lee, S.C., Brinton, E., 2012. Waterproofing crops: effective flooding survival strategies. Plant Physiol. 160, 1698–1709.
Boserup, E., 1965. The Conditions of Agricultural Growth: the Economics of Agrarian Change under Population Pressure. George Allen & Unwin, London.
Brookes, G., Barfoot, P., 2018. Farm income and production impacts of using GM Crop technology 1996-2016. GM Crops Food 8 (3), 156–193.
CFSPH (The Center for Food Security & Public Health), 2010. Drought and Your Crops: Natural Disasters. Iowa State University: CFSPH. http://www.prep4agthreats.org/Assets/Factsheets/Drought-and-Your-Crops.pdf.
Crawford, G.W., Ordish, G., 2017. Origins of Agriculture. ENCYCLOPÆDIA BRITANNICA Retrieved April 13, 2018, from. https://www.britannica.com/topic/agriculture/Pest-and-disease-control-in-crops.
Damkjaer, S., Taylor, R., 2017. The measurement of water scarcity: defining a meaningful indicator. Ambio 46 (5), 513–531.
Dar, M.H., de Janvry, A., Emerick, K., Raitzer, D., Sadoulet, E., 2013. Flood-tolerant rice reduces yield variability and raises expected yield, differentially benefitting socially disadvantaged groups. Sci. Rep. 3 (3315), 1–8.
de Boef, Walter, 2000. Tales of the unpredictable: learning about institutional frameworks

that support farmer management of agro-biodiversity. Wageningen-ur. Promotor: prof. Dr. Ir. N.G. Röling, co-promotor(en): dr. Ir. J.M.M. Engels en Dr. Ir. J.J. Hardon. https://www.researchgate.net/publication/40140333_Tales_of_the_unpredictable_Learning_about_institutional_frameworks_that_support_farmer_management_of_agro-biodiversity.

Desertification Indicator System for Mediterranean Europe, ND. Joint research centre, European soil data centre (esdac). Accessed on May 5, 2019.. https://esdac.jrc.ec.europa.eu/public_path/shared_folder/projects/DIS4ME/indicator_descriptions/irrigation_potential_realised.htm.

Dinar, S., Dinar, A., Kurukulasuriya, P., 2011. Scarcity and cooperation along international rivers: an empirical assessment of bilateral treaties. Int. Stud. Q. 55, 809–833.

Easter, K.W., Huang, Q. (Eds.), 2014. Water markets for the 21st Century, What have we learned? Springer, Dordecht Global Issues in Water Policy #11.

Falkenmark, M., 1986. Fresh water: time for a modified approach. Ambio 15, 192–200.

Falkenmark, M., 1989. The massive water scarcity now threatening Africa – why isn't it being addressed? Ambio 18 (2), 112–118.

FAO (Food and Agricultural Organization of the United Nations) AQUASTAT, 2015. Proportion of Total Water Withdrawal Withdrawn for Agriculture. *(%)* [PDF file]. Retrieved from. http://www.fao.org/nr/water/aquastat/maps/WithA.WithT_eng.pdf.

FAO (Food and Agricultural Organization of the United Nations) AQUASTAT Total renewable water resources (n.d). http://www.fao.org/nr/water/aquastat/data/query/index.html?lang=en [Data file]. Retrieved from.

FAO (Food and Agricultural Organization of the United Nations) AQUASTAT, 2016. Japan. [PDF file]. Retrieved from. http://www.fao.org/nr/water/aquastat/countries_regions/JPN/.

FAO (Food and Agricultural Organization of the United Nations) Statistical Database, 2016a. Crops. [Data file]. Retrieved from. http://www.fao.org/faostat/en/#data/QC.

FAO (Food and Agricultural Organization of the United Nations) Statistical Database, 2016b. Food balance Sheets. [Data file]. Retrieved from. http://www.fao.org/faostat/en/#data/FBS.

FAO (Food and Agricultural Organization of the United Nations) Statistical Database, 2015. Land use. [Data file]. Retrieved from. http://www.fao.org/faostat/en/#data/RL.

FAO (Food and Agricultural Organization of the United Nations)., 2012. Statistical Yearbook 2012. Rome: Food and Agriculture Organization. Retrieved from. http://www.fao.org/docrep/015/i2490e/i2490e00.htm Accessed April 18, 2018.

FAO (Food and Agricultural Organization of the United Nations), 2014. Irrigation areas, irrigated crops, environment. Accessed: April 13, 2018. http://www.fao.org/nr/water/aquastat/didyouknow/index3.stm.

FAO (Food and Agricultural Organization of the United Nations), 2002. The State of Food Insecurity in the World 2001. FAO, Rome.

FAO (Food and Agricultural Organization of the United Nations), 2006. The State of Food Insecurity in the World 2006. FAO, Rome.

FAO (Food and Agricultural Organization of the United Nations), 2017. The State of Food Security and Nutrition in the World 2017: Building Resilience for Peace and Food Security. FAO, Rome.

Giordano, M., Turral, H., Scheierling, S.M., Treguer, D.O., McCornick, P.G., 2017. Beyond More Crop Per Drop: Evolving Thinking on Agricultural Water Productivity. IWMI Research Report 169, Colombo, Sri Lanka.

Griffiths, C.A., Paul, M.J., 2017. Targeting carbon for crop yield and drought resilience. J. Sci. Food Agric. 97 (14).

Hanjra, M.A., Qureshi, M.E., 2010. Global water crisis and future food security in an era of climate change. Food Policy 35, 365–377.

Hayami, Y., Ruttan, V.W., 1985. Agricultural Development: an International Perspective. Johns Hopkins University Press, Boltimore.

Hernández-Sancho, F., Lamizana-Diallo, B., Mateo-Sagasta, J., Qadir, Manzoor, 2015. Economic Valuation of Wastewater - the Cost of Action and the Cost of No Action. United Nations Environment Programme, Nairobi.

Hussain, I., Raschid, L., Hanjra, M.A., Marikar, F., van der Hoek, W., 2001. Framework for Analyzing Socioeconomic, Health, and Environmental Impacts of Wastewater Use in Agriculture. IWMI Working Paper 26. International Water Management Institute, Colombo, Sri Lanka.

IPCC, 2013. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Climate Change 2013: the Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA 1535 pp.

ISAAA, 2008. ISAAA pocket K No. 32: biotechnology for the development of drought tolerant crops. Retrieved April 13, 2018. http://www.isaaa.org/resources/publications/pocketk/32/default.asp.

ISAAA, 2015. ISAAA brief 51-2015: executive summary. *Documented Benefits of GM crops - pocket K*. Retrieved June 18, 2018. www.isaaa.org/resources/publications/briefs/51/executivesummary/default.asp.

ISAAA, 2016. Global status of commercialized Biotech/GM crops: 2016. ISAAA brief No. 52. Accessed April 11, 2018. https://www.isaaa.org/resources/publications/briefs/52/download/isaaa-brief-52-2016.pdf.

Jarvis, D., Rao, R.V., 2002. Issues in the Assessment, Management and Conservation of Crop Diversity in Agroecosystems in a Changing World. [PDF document]. Retrieved from. https://www.researchgate.net/publication/285959354_Issues_in_the_assessment_management_and_conservation_of_crop_diversity_in_agroecosystems_in_a_changing_world?fbclid=IwAR1-QJZfxP7sUzSc46LjjUnnjHSBxF8ozBRC3rUaNc6r11o6wcd7VkyFHOc.

Karimov, A., Smakhtin, V., Mavlonov, A., Borisov, V., Gracheva, I., Miryusupov, F., Djumanov, J., Khamzina, T., Ibragimov, R., Abdurahmanov, B., 2013. Managed Aquifer Recharge: the Solution for Water Shortages in the Fergana Valley. IWMI Research Report 151. International Water Management Institute (IWMI), Colombo, Sri Lanka 51pp.

Kawashima, C.G., Guimarães, G.A., Nogueira, S.R., MacLean, D., Cook, D.R., Steuernagel, B., 2016. A pigeonpea gene confers resistance to asian soybean rust in soybean. Nat. Biotechnol. 34, 661–665.

Liang, X., van Dijk, M.P., 2011. Economic and financial analysis on rainwater harvesting for agricultural irrigation in the rural areas of beijing. Resour. Conserv. Recycl. 55 (11), 1100–1108.

Liang, C., 2016. Genetically modified crops with drought tolerance: achievements, challenges, and perspectives. In: In: Hossain, M.A. (Ed.), Drought Stress Tolerance in Plants, vol. 2. Springer, pp. 531–547.

Loucas, Holly, 2017. "How GMOs Are Made." *Are GMOs Harmful | Corteva Agriscience*, Corteva, 1 Feb. www.corteva.com/resources/blog/blog-articles/how-gmos-are-made.html.

Madani, K., Dinar, A., 2012. Cooperative institutions for sustainable common pool resource management: application to groundwater. Water Resour. Res. 48 (9). https://doi.org/10.1029/2011WR010849.

Magelgaard, K., 2012. Why Population Matters to Water Resources. Population Action International, Washington DC, USA.

Maliva, R.G., 2014. Economics of managed aquifer recharge. Water 6 (5), 1257–1279.

Malthus, T.R., 1798. An Essay on the Principle of Population. Cambridge University.

Mann, Charles, C., 2018. Can Planet Earth Feed 10 Billion People? the Atlantic. March.

McLaughlin, D., Kinzelbach, W., 2015. Food security and sustainable resource management. Water Resour. Res. 51, 4966–4985. https://doi.org/10.1002/2015WR017053.

McNeill, K., Macdonald, K., Singh, A., Binns, A.D., 2017. Food and water security: analysis of integrated modeling reforms. Agric. Water Manag. 194, 100–112.

Murray, D.,H., Clarke, M.B., Ronning, D.A., 2013. Estimating invertebrate pest losses in six major Australian grain crops. Aust. J. Entomol. 52 (3), 227–241.

Nelson, R., Hanks, T.W., Wisser, R., Kurti, P.B., 2018. Navigating complexity to breed disease-resistant crops. Nat. Rev. Genet. 19, 21–23.

Ostrom, E., 2010. Beyond markets and states: polycentric governance of complex economic systems. Am. Econ. Rev. 100 (3), 641–672.

Pathak, T.B., Maskey, M.L., Dahlberg, J.A., Kearns, F., Bali, K., Zaccaria, D., 2018. Climate change trends and impact on California agriculture: a detailed review. Agronomy 8 (25), 1–27doi. https://doi.org/10.3390/agronomy8030025.

Pingali, P.L., 2012. Green revolution: impacts, limits, and the path ahead. Proc. Natl. Acad. Sci. 109 (31), 12302–12308.

Qaim, M., Kouser, S., 2013. Genetically modified crops and food security. PLoS One 8 (6), e64879.

Raskin, P.D., Hansen, E., Margolis, R.M., 1996. Water and sustainability: global patterns and long-range problems. Nat. Resour. Forum 20, 1–15.

ReliefWeb, 2018. China: floods. reliefweb.int/disaster/tc-2018-000110-chn.

Rosegrant, M.W., Ringler, C., Zhu, T., 2009. Water for agriculture: maintaining food security under growing scarcity. Annu. Rev. Environ. Resour. 34, 205–223.

Scheierling, S.M., Tréguer, D.O., 2018. Beyond Crop Per Drop: Assessing Agricultural Water Productivity and Efficiency in a Maturing Water Economy. International Development in Focus, Washington, DC World Bank. https://openknowledge.worldbank.org/handle/10986/29922.

Scheierling, S.M., Treguer, D.O., 2016. Investing in adaptation: the challenge of responding to water scarcity in irrigated agriculture. Fed. Reserv. Bank Kans. City Econ. Rev. Econ. Rev. 75–100.

Schmidhuber, J., Tubiello, F.N., 2007. Global food security under climate change. Proc. Natl. Acad. Sci. 104 (50), 19703–19708.

Siebert, S., Kummu, M., Porkka, M., Döll, P., Ramankutty, N., Scanlon, B.R., 2015. A global data set of the extent of irrigated land from 1900 to 2005. Hydrol. Earth Syst. Sci. 19, 1521–1545.

Shyam, N., Johnson, J.W., Wang, C., 2013. Efficiency of irrigation water use: a review from the perspectives of multiple disciplines. Agron. J. 105 (2), 351–363.

Turral, H., Burke, J., Faures, J.-M., 2008. Climate Change, Water and Food Security. FAO Water Reports 36. FAO, Rome.

U.S. Environmental Protection Agency, 2016. Future of climate change. December 27. https://19january2017snapshot.epa.gov/climate-change-science/future-climate-change_.html Retrieved from.

UCSUSA (Union of Concerned Scientists), 2012. Monsanto's 'DroughtGard' corn barely a drop in the bucket. June 5. www.ucsusa.org/news/press_release/monsantos-droughtgard-corn-0391.html#.WwbfJkgvzIU Accessed June 18, 2018.

United Nations, Department of Economic and Social Affairs, Population Division, 2015. World prospects (2015 revisions). Accessed March 22, 2018. http://www.un.org/en/development/desa/publications/world-population-prospects-2015-revision.html.

USDA (U.S. Department of Agriculture) Food security. n.d. https://www.usda.gov/topics/food-and-nutrition/food-security Accessed May 2018.

Wang, J., Huang, Q., Rozelle, S., 2016. Impacts of groundwater markets on agricultural production in China (Chapter 7) In: Managing Water on China's Farms, Institutions, Policies and the Transformation of Irrigation under Scarcity. Elsevier, pp. 123–132.

Ward, F.A., Pulido-Velazquez, M., 2008. Water conservation in irrigation can increase water use. Proc. Natl. Acad. Sci. 105 (47), 18215–18220.

Wheeler, T., von Braun, J., 2013. Climate change impacts on global food security. Science 341, 508–513.

Winnpenny, J., Heinz, I., Koo-Oshima, S., Salgot, M., Collado, J., Hernandez, F., Torrichelli, F., 2010. Thewealth of waste: The economics of wastewater use in agriculture. FAO, Land and Water Division, Rome Water Report, AGRIS No. 35.

World Resources Institute (n.d). http://www.wri.org/blog/2013/12/global-food-challenge-explained-18-graphics Accessed May 13, 2018.

Xu, H., Wu, M., 2017. Water Availability Indices – A Literature Review. U.S. Department of Energy, Argonne National Laboratory, Energy Systems Division Report ANL/ESD-

17/5, February.

Yang, X., Hu, R., Yin, H., Jenkins, J., Shu, S., Tang, H., … Tuskan, G.A., 2017, December 01. The kalanchoë genome provides insights into convergent evolution and building blocks of crassulacean acid metabolism. Nat. Commun. 8 Article number 1899.

Yuan, T., Fengmin, L., Puhai, L., 2003. Economic analysis of rainwater harvesting and irrigation methods, with an example from China. Agric. Water Manag. 60 (3), 217–226.

Zilberman, D., Lipper, L., McCarthy, N., Gordon, B., 2018. In: Lipper, L., McCarthy, N., Zilberman, D., Asfaw, S., Branca, F. (Eds.), Innovation in Response to Climate Change. Springer and FAO, Berlin, pp. 49–74.