Industry note: Irrigated agriculture under climate change

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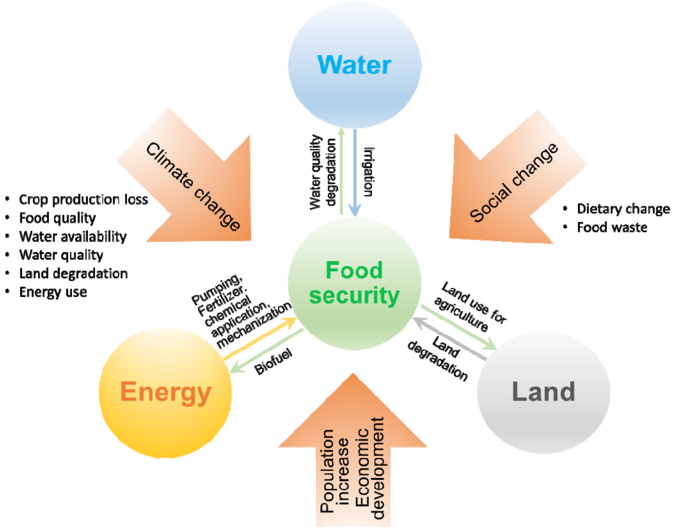
1 Introduction

Irrigated agriculture is vital for global food security which is impacted by a multitude of factors. Figure 1 sketches a framework illustrating the factors that affect food security, including the interactions and feedbacks between land, water, and energy systems, which constitute the water-food-energy-land nexus. Changes in these four systems are driven by population increase, economic development, social changes associated with the rising standard of living (dietary changes and food wastage), and climate change. Both climate and non-climate stresses are impacting food security. This paper provides a qualitative description of factors that affect food security and highlights the role of irrigated agriculture in ensuring future food security.

2 Factor affecting food demand

The world population took about four hundred years to grow from 0.4 billion in the fifteenth century to 1 billion by 1800, then to 1.6 billion by 1900, and to 2.5 billion by 1950. However, it tripled by 2020 with 7.8 billion and is expected to reach 9.7 billion by 2050 and 10.9 billion by the turn of 2100, according to the medium-variant projection from the United Nations (UN, 2019). Consequently, world food production will have to increase by 24% by 2050 and by 40% by 2100 at the 2020 level if there was no change in consumption patterns.

Figure 1 Water-food-energy-land nexus in irrigated agriculture (see online version for colours)



Income growth is another key driver of food demand, in which income growth indicates improved living standards and increasing per capita demand for agricultural products as diets shift to fruits, vegetables, and animal-based products. van Dijk et al. (2021) noted that the total global food demand would increase by 35% to 56% between 2010 and 2050, equivalent to an increase by 14–26% between 2020 and 2050. If climate change is considered, the food demand increase from 2010 to 2050 will be slightly changed (i.e., 30%~62%). Fukase and Martin (2020) estimated that the per capita demand growth would increase by 102% from 2010 to 2050 (or equivalently by 65% from 2020 to 2050). According to the Food and Agriculture Organization (FAO), global mean per capita food consumption increased from 2,200 kcal per capita per day in 1961 to 2,881 kcal per capita per day in 2013 with an average increase rate of 6% per decade. Nearly 630 million people, who account for 8% of the total world population, were undernourished every year from 2010 to 2019.

On average, 14% of food was wasted by consumers and 12% was lost during the pre-harvest processing, including harvesting, transportation, storage, distribution, during 2001–2017. FAO (2011) reported that nearly one-third of the edible food was wasted globally, equivalent to 1.3 billion tons per year. The per capita food loss estimated by FAO in 2007 was about 280–300 kg/year in Europe and North America and was 170 kg/year in Sub-Saharan Africa. European and North American consumers alone wasted roughly 168–204 million tons of food in 2020, enough to feed 460–560 million individually annually, assuming that 1,000 g per person per day is required to maintain a 2,000 kcal daily healthy diet.

3 Food production

About 49% of the global ice-free land surface is agricultural land, of which about 24% is cropland which provides 83% and 63% of global calories and protein supply, respectively. To meet the growing food demand, global cropland has increased by 23% between 1961 and 2018 at the expense of other lands, including forest, grassland, and wetland. Based on FAO's estimation, the net cropland increase would be only 0.7 M km^2 by 2050, a result of a 1.32 M km^2 increase in developing counties (mostly in sub-Saharan Africa and Latin America) and a 0.63 M km^2 decrease in developed countries (Alexandratos and Bruinsma, 2012). Since the area of rainfed cropland was relatively stable during this period, irrigated cropland contributed most of the total cropland increase, and its proportion increased from 12% in 1961 (1.6 M km^2) to 22% (3.4 M km^2) in 2018. Siebert and Doll (2010) estimated that irrigated cropland contributed about 43% of total cereal production from 1990 to 2002. With the increased proportion of irrigated land, increased cropping intensity, new crop varieties adoption, and fertiliser application, global food production almost tripled during this period. Cereal production showed the most dramatic increase by 270%. As the availability of cropland continues to stagnate, increasing the yield from existing cropland is the primary solution to meet the future demand challenges. Amidst various ways to increase crop yield, irrigation is of paramount importance.

The expansion of irrigated cropland has greatly improved global food production. Siebert and Doll (2010) found that if no irrigation water were applied, the global cereal production would decrease by 47% on irrigated cropland, corresponding to a 20% of total production loss. The global production loss would be relatively high for date palms (60%), rice (39%), cotton (38%), citrus (32%), and sugarcane (31%). The global mean cereals yield from irrigated cropland (442 Mg km^{-2}) was 1.7 times of that from rainfed cropland (266 Mg km^{-2}). Africa has the highest potential to increase its production through irrigation (by 320%), followed by Oceania (by 228%), Europe (by 98%), Asia (by 91%), and Americas (57%). Currently, irrigated cropland only accounts for a small proportion of total cropland in Europe (4%), Africa (9%), Oceania (11%), and Americas (13%). The potential for expansion of irrigated areas is still large in water-rich regions, especially in Sub-Saharan Africa and Latin America. However, in some countries in North Africa, Central Asia, West Asia, South Asia, and East Asia, further expansion of irrigated land is limited since these countries have reached or close to their potential.

4 Water requirement for irrigated agriculture

The potential for future expansion of irrigated agriculture is dependent on the availability of renewable water resources for irrigation. Irrigation water demand accounts for nearly 70% of global anthropogenic freshwater demand (FAO, 2016) and is by far the largest water use sector in the world, especially in Africa, Asia, and Latin America. At the same time, water resources for irrigated agriculture face multiple challenges, including growing food demand, increasing global mean temperature, and changing precipitation patterns under climate change, as well as competition from domestic and industrial users because of population growth and economic development. Globally, renewable water resources are adequate for irrigation, e.g., 6% used for irrigation, but there are already some regions with severe water shortages, in particular in Northern Africa, where irrigation withdrawal exceeds renewables by 70% due to the overdraft of groundwater. Half or more of the renewable resources are used for irrigation in Western (47%), Central (48%), and South Asia (55%). Even in regions with plenty of water resources, some countries in Central America and the Caribbean may have a higher percentage of irrigation withdrawal. Irrigation water use in Libya, Saudi Arabia, Yemen, and Egypt even exceed their renewable resources. Therefore, improving irrigation efficiency is a possible solution to relieve water scarcity.

Irrigated cropland in most countries relies heavily on surface irrigation, which usually has about 30–35% water use efficiency. For sustained crop productivity in water-scarce regions, irrigated cropland will have to shift to more efficient irrigation technologies, e.g., sprinkler, drip, or micro-irrigation whose efficiency can be as high as 80–95%. However, sprinkler and drip irrigation systems are more energy-intensive and are dependent on local energy availability. Proper system design and management are required to ensure both water and energy use efficiency in irrigated agriculture.

5 Impact of climate change

Climate change affects food security through rising air temperature, variation in precipitation patterns, higher atmospheric CO_2 concentration, and more frequent extreme weather. From an agricultural point of view, increasing temperature leads to higher evaporation and evapotranspiration, showing negative effects on irrigation water use. Higher temperature and atmospheric CO_2 concentrations and changes in precipitation patterns pose a challenge for agricultural production, irrigation, and management and operation of irrigation systems, causing changes in crop yield.

Climate change also exacerbates land degradation, leading to food and nutritional insecurity. Higher temperature and enhanced wind speed under global warming can accelerate wind-induced soil erosion. Heavy rainfall and more frequent flooding increase water erosion of topsoil and the loss of topsoil decreases soil fertility, thereby having negative impacts on crop yield. Climate change induces intensified rainfall increasing soil leaching; can modify soil salinity in arid, semi-arid, and coastal areas; exacerbates desertification; and alters water quality through biochemical processes, negatively impacting crop yield. Warmer water temperatures tend to weaken the dilution effects of water bodies, decreases the ability to retain dissolved oxygen, and exacerbates water quality. Drought is enhanced under climate change, affecting the hydrological processes at the basin level, leading to increased pollution concentrations, delayed recovery from acidification, and enhanced nitrogen mineralisation. As temperature increases, the previous frozen soils may release toxic heavy metals, which can contaminate food and water resources through plants, water, and wildlife.

6 Future water availability

Climate change perturbs the terrestrial hydrologic cycle and affects both water supply and demand. However, current projections of future climate change impacts on available water resources have high uncertainty, primarily due to the large variations in rainfall projections from general circulation models (GCMs) and the uncertainties from global hydrological models (GHMs) used for the assessment of water resources. The influence of climate change is highly geographically dependent. Hagemann et al. (2013) found that available water resources were expected to increase in most catchments, but great decreases were anticipated in Central and Southern Europe, the Middle East, Southern Africa, the Mississippi River Basin, Southern Africa, South of China, and Southeast Australia.

Climate change also affects irrigation potential. Elliott et al. (2014) suggested that some currently heavily irrigated regions like Western and Central Asia, Northern China, North Africa, Western US, and Mexico were expected to have no irrigation potential in response to the insufficient water resources in a warming climate. This would lead to a conversion of 20–60 Mha irrigated cropland to rainfed, and, consequently, 600–2,900 Pcal food production would be lost due to the yield decrease under rainfed conditions. However, freshwater abundance in regions like Northern/Eastern US, Europe, parts of South America, and South Asia may suffice further expansion of irrigated cropland. Since climate change tends to increase potential irrigation water consumption as temperature gets warmer in the future, it tends to increase irrigation water scarcity.

7 Food production potential

Climate change affects crop yields through increased air temperature, elevated CO_2 emissions, changing water availability and quality, and accelerating land degradation. In Australia, water-limited crop yield potential declined by 27% between 1990 and 2015 due to rising temperature and decreased rainfall (Hochman et al., 2017). Tao et al. (2014) found climate change had a positive effect on wheat growth in Northern China and a negative effect in Southern China from 1981 to 2009 because of different responses of precipitation to varying climate. The wheat yields in India during the same period (1981–2009) reported a 5.2% loss due to warmer temperatures (Gupta et al., 2017). At the global scale, Izumi et al. (2018) reported that global mean yields of wheat, maize, and soybeans decreased by 1.8–4.5% from 1981 to 2010 due to climate variations, even considering the positive effect of CO_2 fertilisation and climate adaptations.

In low latitude regions (tropical regions), the production of crops like maize and wheat is projected to be negatively affected by climate change, even under moderate temperature increase (1 to 2°C), given that the temperature of many tropical regions is very close to the threshold for crop growth. In mid- and high-latitude regions, rainfed crop yields of maize, wheat, and sugar beets, etc., are anticipated to increase slightly with moderate-to-medium increase (about 1–3°C) in temperature, along with CO_2 increase and rainfall changes. The projected production losses in the low latitude regions are especially pronounced without explicit nitrogen fertilisation.

To evaluate the global potential for irrigation-based adaptation, Elliott et al. (2014) found that without the expansion of irrigated cropland, maize, soybean, wheat, and rice production in total calories were projected to decrease by 8%–24% (400–1,400 Pcal) when accounting for the CO_2 fertilisation effects or 24%–43% (1,400–2,600 Pcal) if no CO_2 fertilisation effects. When assuming maximum conversion of current rainfed cropland to irrigated, 57% of the median losses (730 Pcal) could be ameliorated by the expansion of irrigation by 2090. However, some heavily irrigated regions, e.g., Northern China; Western US; and South, West, and Central Asia, will suffer a loss of 600–2,900 Pcal (10–48%) due to the conversion of 20–60 Mha of irrigated cropland to rainfed because of limited available freshwater.

8 Conclusions

Global food production faces challenges from limited cropland availability, limited water availability, and the detrimental effects of climate change on crop yield. In response to the increase in food demand, food production will have to increase by 24% by 2050 and by 40% by 2100. Irrigated cropland plays a vital role in compensating for the negative climate change impacts on current crop production. Nevertheless, irrigated cropland will be curtailed due to the limited available freshwater which is anticipated in some heavily irrigated regions, e.g., Northern China; Western US; and South, West, and Central Asia. Improved irrigation capacity and technology efficiency in currently irrigated regions are needed to ensure future food security. Drip and sprinkler irrigation systems are to be expanded to save both water and energy. Projections of crop yield losses under changing climate still exhibit large variations, primarily due to the uncertainties from models used and large ranges of estimations of climate change effects. Therefore, there is a need for more studies on understanding climate change and its adverse impacts on water resources availability and crop production.

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