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Irrigated Agriculture as an Adaptation Strategy Against Climate Change: A Review

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Abstract

Agriculture evolved to increase crop productivity and diminish plague effects. As a negative outcome of the human footprint by agriculture and industrialization, overall economic practices have led to substantial alterations in the environment (*i.e.*, greenhouse gas production, elevated atmospheric temperature, more extreme climatic events), collectively known as climate change. The fast-changing environment due to climate change is most common in the tropics, the impacts of this phenomenon are perceived in different regions of the world, where most agricultural activity occurs. These facts reinforce the requirement for diminishing climate change producing activities and implementation of adaptive practices for long-term agricultural productivity and sustainability. Albeit may sound counter-intuitive, agroecological systems and traditional knowledge may provide alternatives to mitigate climate change effects in the context of agriculture. This review comprehensively describes the development of irrigated agriculture, major effects of climate change on irrigation, and further explores alternative practices stemming from agroecological systems or traditional knowledge, which could improve agricultural productivity and sustainability. Among some strategies, it is proposed to establish climate risk planning, agricultural producers must modify the application of their inputs to adjust to the new water and thermal requirements; implement conservation techniques to reduce the loss of soil moisture and thus ensure the development of crops in a drier and warmer environment as indicated by climate change projections. Likewise, the implementation of varieties tolerant to water stress is one more adaptation action that would allow continuing cultivating in lower regions, where the largest irrigated area is concentrated and which would receive the greatest impact from an increase in temperature. In this way, it will be necessary to implement new approaches, technologies and policies to learn from the past, following the new climate scenarios, conserving and making rational use of natural resources.

Keywords: agriculture, agroecosystem, climate change, sustainability

1. Introduction

Agriculture is a core feature of human activity. Humans initially met their needs by hunting and gathering (*e.g.*, water, fibers, wood). Despite the current view of the transformative effect of such shift from hunting/gathering to agriculture, it remains unclear what motivated human societies for this transition (Maisels, 2003; Weisdorf, 2005). Later, humans developed greater impact on natural landscapes, such as deforestation (Foley et al., 2005), land management, and the domestication of plants and livestock. The exploitation of natural resources for agriculture began between 5,000-10,000 years ago, which lead to the dawn of human civilization (Weisdorf, 2005). The advent of agriculture and livestock production represents a breakthrough, known as the Neolithic revolution (Fuller & Stevens, 2019), thus sustaining food production for human populations under accelerated growth and their accumulating material wealth (Maisels, 2003; Weisdorf, 2005). Therefore, these conditions allowed humans to establish long-term communities at defined places. The advent of agriculture also led to the urban revolution, which contemplated the exponential growth of numerous cities and the expansion of non-farming activities (unrelated to food production) that led to work specialization, trading and development of new technologies such as textile manufacturing and metallurgy (Fuller & Stevens, 2019).

Agriculture land has expanded worldwide and now occupies one third of ice-fee land (Ramankutty et al., 2018). This growth was most notable over the last three centuries, with 1.2 billion hectares (ha) as novel farmland during this period time (Klein Goldewijk & Ramankutty, 2004). Based on spatially-explicit land use and land cover change, global data sets revealed that the landscape dedicated to cropland and pasture area grew five-fold within the timeframe from 1700 to 2007 (Ramankutty et al., 2018). Hence, agriculture expansion largely agreed with economic factors such as areas of intense industrialization and European settlement in other continents (Ramankutty et al., 2018). Farmland worldwide now spans an area of 1.8 billion ha, thus including agriculture, livestock production, and other types of cultivation (Klein Goldewijk & Ramankutty, 2004).

Food production increased by ~50% in the last two decades (from 2000 to 2018), thus reaching 9.2 billion tons, while four crops (*i.e.*, sugar cane, maize, rice, and wheat) were responsible for half of such production (FAO, 2020). In turn, agricultural land declined by 78 million ha within the same timeframe. Nonetheless, the demand for food continues to rise (Madramootoo & Fyles, 2010) while hunger increases, since 690 million people were undernourishing in 2019. This represents 60 million people more than 2014 (FAO, 2020). Hunger concentrates on Asia and African continents (and other developing countries), further complicating the relationship between food production and demand.

Another significant pressure to increase food demand is urbanization that associates with higher economic conditions and the request for high protein, more processed, calorie-rich, and micronutrient rich diets (Madramootoo & Fyles, 2010). These technology-driven foods require more water for their production. Collectively, these facts threaten the concept of food security, which is a balance between food supply and expected demand (Pretty, 2008). The economic crisis also highlighted the current fragility of food security (Madramootoo & Fyles, 2010). Alongside the expected increase in human population to nine-ten billion by 2050 will also pose an even greater demand for food production (Ramankutty et al., 2018; Leisner, 2020), particularly in developing countries that contribute to population growth (Pretty, 2008). In sum, despite a steady growth of agricultural output, there is a demand to increase food production for the upcoming decades (Ramankutty et al., 2018).

This review aimed was to describe irrigation as a major advance in agricultural practices. Secondly, to enumerate the effects of climate change on irrigated agriculture, and further advocate the potential of concepts or practices from agroecological systems and traditional knowledge to circumvent (at least partially) such detrimental effects under growing demands for food under sustainable conditions.

2. Irrigation Is a Key Technology for the Expansion of Agriculture

Technology paved the way for the expansion of agriculture. For instance, crop irrigation was (and still is) a highly successful advance for crop productivity. The controlled use of water resources permitted the expansion of agriculture and human populations to areas of limited or inconstant surface water and rainfall (Gulhati & Smith, 1967). This technology dates back over 5,000 years ago, as evidenced by basin irrigation developed in Egypt. European explorers also found agriculture and small-scale irrigation on the American continent. Initial irrigation systems were based on canals, tanks or aqueducts which varied substantially in capacity and extension. There are ancient irrigation systems that remain under use as initially designed or with adaptations. The impact of irrigation on crop yields was such that, it frequently overshadowed the demands for other agronomic practices, thus including soil amelioration and drainage (Gulhati & Smith, 1967).

Irrigation systems faced constant technological developments. Irrigation systems are gravity-flow or pressurized. Gravity-flows are channels delivering the water across the field, as described above. The amount and uniformity of water infiltration depends upon soil characteristics and the irrigator control of water supply to channels. Approximately 30-40% of irrigated areas rely on dams. The American west offers an example of step-wise innovation on the application of irrigation toward pressurized systems: wind-driven pump, gasoline engine pump, deep-well drilling, and head sprinkler systems for abundant and water supply. Pressurized systems transport the water using pressurized tubes and deliver it by sprinklers or small orifices. These systems provide precise control of water delivery, which should consider soil traits and climatic conditions. Pressurized systems are much more expensive than gravity-flow systems. Therefore, the increase in crop productivity must be proportional to the economic investment.

Irrigation systems became more sophisticated and efficient over time, thus leading to their expansion worldwide (Madramootoo & Fyles, 2010). Modern large-scale irrigation began worldwide in the 19th century, including countries such as India and Egypt. In the following century, some irrigation projects reached areas of million ha

(Gulhati & Smith, 1967). Irrigation faced an expansion during the 1960s and 1970s to combat hunger and malnutrition, which contributed to initiating the "green revolution" (Madramootoo & Fyles, 2010; Ramankutty et al., 2018). Irrigation also allowed farmers to harvest two or three crops per year, instead of one (Madramootoo & Fyles, 2010). Further than increasing crop yields (Ramankutty et al., 2018), it also allowed crop diversification by permiting the introduction of plants that demanded more water than was offered by rainfall (Madramootoo & Fyles, 2010).

Nowadays, 17% of the world's agricultural land applies irrigation and these areas represent 40% of the global food production (Bonfils & Lobell, 2007). Most current irrigated croplands are in Asia (India, Pakistan, and China) and the USA (Bonfils & Lobell, 2007). The irrigated areas have grown around 2% per year in these countries over the last half-century (Bonfils & Lobell, 2007). Over 70% of irrigated areas are found in Asia, which contemplates only 33% of the agricultural area of the world (Madramootoo & Fyles, 2010). Irrigation contributed substantially to combating hunger by increasing crop yields (Madramootoo & Fyles, 2010).

Further developments in agricultural practices, such as the association of irrigation and fertilizers flourished crop productivity (Gulhati & Smith, 1967). The development of chemical fertilizers brought about another boost to agricultural productivity. Further, these advances allowed the expansion of agriculture to areas of soil with lower fertility and rainfall. Plant breeding allowed the development of more productive cultivars, which delivered higher production yields or adapted to more challenging environments (abiotic stress) or plagues (biotic stress).

3. The Impact of Climate Change and Management on Irrigated Agriculture

Human activity also led to negative impacts in agricultural output. Progress on industrialization and intensive deforestation culminated in elevated atmospheric greenhouse gas concentrations, which triggered global shifts in climatic conditions (Anderson et al., 2020). These environmental fluctuations known as climate change, are evidenced by a steady increase in global land temperature across centuries, most notably from the preindustrial period (late 19th century) onward (Anderson et al., 2020). The world faced a global mean temperature increase of ~0.7 °C in the last century (Liu et al., 2012; Pacifici et al., 2015), which represents the greatest increases in the last millennium and should increase more ~4.3 °C by 2100 (Pacifici et al., 2015). The environmental challenge brought by climate change has profound and multivariate consequences. It causes changes in season length or timing, alteration in the distribution of agricultural areas, and greater frequency of extreme weather events are major concerns associated with climate change. In certain regions of Mexico, there are some cases in which climate chance is perceived related with phenomena such as droughts and wind that affect agriculture (Rosales et al., 2020). Climate change provoke the reduction of watercourses, while it also increases evapotranspiration, and enhancing salinization of costal aquifers due to rising sea levels (Bolaños & Betancurt, 2018).

Urban areas, ecosystems, industry, and agriculture compete for water. Pollution and salinity further diminish the quality of available water. These facts highlight the lowering availability of fresh water per capita around the world (Madramootoo & Fyles, 2010). The extensive use of water for agriculture led to its shortage worldwide, thus leading to shortages in urban and other population-dense areas, which placed pressure on water use that may threaten the irrigation supply (Madramootoo & Fyles, 2010). More than a billion people suffer from water scarcity, which is why they settle in the river basins (Madramootoo & Fyles, 2010).

Agriculture itself contributed to environmental degradation and climate change (Ramankutty et al., 2018). Land use change within the last 150 years generated nearly half the amount of carbon emissions than fossil fuels. This modulation in land use affects several factors contributing to local climate conditions, such as surface reflectivity, heat absorption, and water evaporation. Furthermore, greenhouse gas emissions by agriculture and livestock production combined increased by 16% within the last two decades (from 2000 to 2017), and enteric fermentation (which occurs in the digestive system of ruminant livestock species) is responsible for 40% of such emissions (FAO, 2020). The reduction of agriculture productivity caused by climate change is unequivocal, as demonstrated by lower production yields in both annual (*e.g.*, maize) and perennial fruit crops (Tripathi et al., 2016; Ramankutty et al., 2018; Lu et al., 2019; Anderson et al., 2020). Climate change associated events cause reductions in crop nutritional content in a species-specific manner. However, climate change does not bring about only detrimental impacts on agriculture. The elevation of CO2 levels alone in the atmosphere may increase plant photosynthesis potential that may result in greater agronomic production (Goudriaan & Zadoks, 1995; Fischer et al., 2005; Anderson et al., 2020; Leisner, 2020), albeit high temperature and other climate change associated factors counteract this potential (Fischer et al., 2005).

A combination of climate change and non-sustainable management practices threatens the future of irrigated agriculture (Figure 1). These conditions complicate the utilization of irrigation under four core factors, namely diminishing water resources, waterlogging, causing land erosion, and soil salinization. These factors alongside the competition for water with other applications alongside ecosystem damage collectively led to public criticism of irrigation agriculture. Not surprisingly, the expansion of irrigated agriculture diminished from ~2% per year in the 1960s to < 1% in the 1990s (Madramootoo & Fyles, 2010). This situation occurred because the environmental and social consequences of the large irrigation systems were questioned, so investments decreased.

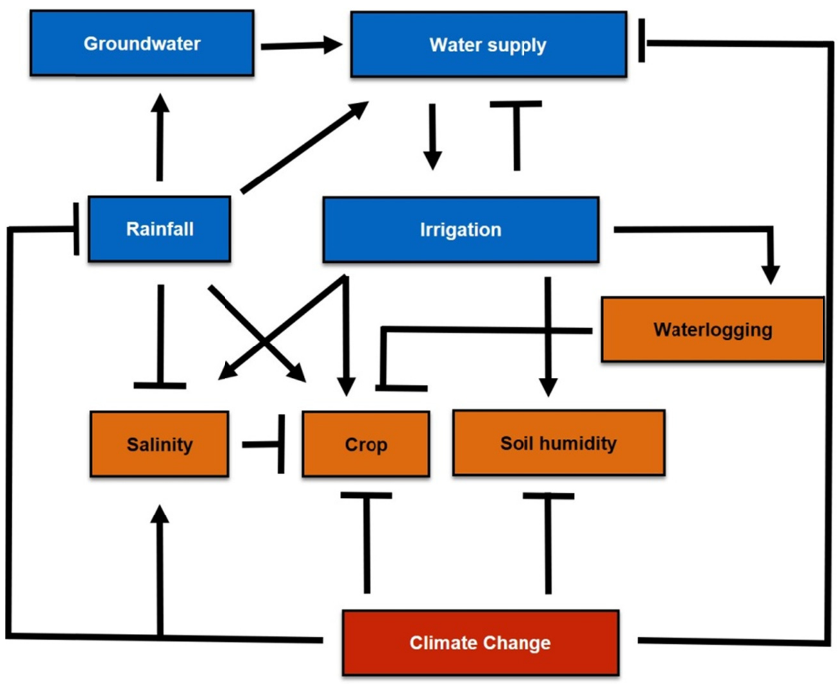

Figure 1. The context of irrigated agriculture considering water supply and climate change

Irrigation suffers from climate change effects, due to its dependency on water supply, which is finite, constantly diminishing, and under growing demand. This water shortage is due to fluctuations in rainfall or stream-flow timing due to climate change and the unsustainable use of groundwater or surface water (Ramankutty et al., 2018). Agriculture is responsible for 70-92% of the water use in the world (Madramootoo & Fyles, 2010; Ramankutty et al., 2018). Around 2% of the planet's surface is covered by irrigated crops (FAO, 2020), which demands 64-90% of water usage (Ramankutty et al., 2018; López-Felices et al., 2020). Therefore, irrigated agriculture has an impact on climatic conditions at both local and global scales. Irrigation associated with deforestation leads to climatic changes at a local scale (Foley et al., 2005). Counter-intuitively, it became clear that such massive irrigated land also has a cooling effect and partially mitigates climate change effects on a global scale (Bonfils & Lobell, 2007), particularly in regions of limited rainfall. The slower growth of irrigated areas will likely reduce its impact on climate change effects.

Groundwater (subsurface) is the main place of stored freshwater (Taylor et al., 2013; Cuthbert et al., 2019). The use of underground water for agriculture doubled in thirty years and fueled the global expansion of agriculture (Madramootoo & Fyles, 2010). It is a valuable source of water in places without surface water or it declined over time (Madramootoo & Fyles, 2010). However, irrigation projects frequently explore groundwater to an extent that cannot replenish. This fact lowers the water table and jeopardizes irrigation projects. Crops used for biofuel production (*e.g.*, sugar cane, corn) require high supplies of water and both fertilizers and pesticides (Madramootoo & Fyles, 2010). The disposal of drainage water with potentially toxic compounds is also much ignored. Agrochemicals may flow to water streams or aquifers. It may not affect the potential use of water for agriculture, albeit not suitable for human consumption and may endanger wildlife. Further, disposal of hazardous waste is under strict regulation in many countries and requires labor instance and costly practices. Therefore, the social decision to restrict water usage for agriculture may affect the future of irrigation. However, underground irrigation is proposed as an alternative to increase water productivity in agriculture due to it minimizes surface evaporation and increases the efficiency of water supply in the root of the plants (Lucero-Vega et al., 2017). The adequate management of water in irrigation is paramount to both crop viability and the preservation of soil traits. If irrigation exceeds the demand of the crop and soil infiltration potential, water accumulates and may cause waterlogging (flooding), it was added as well as a certain impact on emissions and the GEI balance. Waterlogging effects are complex and variable, which may be due to many factors, thus including geography, water dynamics, and irrigation (Shaw et al., 2013; Liu et al., 2021b). It has a substantial negative impact on agriculture in ~16% of cultivated areas worldwide (Ahsan et al., 2007; Zhou et al., 2020). Waterlogging can reduce crop productivity by up to 70% (Ploschuk et al., 2020), most notably during crop heading (Liu et al., 2021). Plants need water throughout their life cycle but in excess can lead to stress due to diminished gas exchange between the soil and atmosphere (Zhou et al., 2020) and increased root diseases (Anderson et al., 2020). Oxygen diffusion in water is much lower the in the atmosphere (Pedersen et al., 2013; Liu et al., 2021a), which affects the oxygenation of plant tissues and ultimately impairs cellular aerobic processes (Voesenek & Bailey-Serres, 2015). The absence of oxygen leads to adaptation of cellular processes to anaerobic fermentation and accumulation of toxins (Xuewen et al., 2014). Climate change may increase waterlogging when it increases rainfall (Liu et al., 2021a) or by leading to hotter days and anticipating flowering (Liu et al., 2021b).

Interactions among water, climate change, and soil erosion are complex (Nearing et al., 2004). Agriculture is a major driver of soil erosion due to plowing, deforestation, and unsustainable management practices (Montgomery, 2007; Borrelli et al., 2020). Soil erosion causes nutrient loss, diminishes carbon storage, and lower fertility (Quinton et al., 2010). Erosion originates from surface water, gullies, wind, and riverbanks (Borrelli et al., 2020). It removes the upper area of the soil that contains most of the organic matter and begins with the overland flow of water, thus transporting the soil. The removal of surface soil exposes deeper soil layers with much lower infiltration rates and agricultural potential. Land use and climate change are the major factors driving soil erosion (O'Neal et al., 2005; Borrelli et al., 2020). Simulations suggest that climate change may increase soil erosion by 30-66%, particularly in the tropics (Borrelli et al., 2020). The increased rainfall caused by climate change may increase soil erosion by water. Although available mitigating strategies (adequate management practices for soil conservation) will probably not suffice to overcome climate change effects, these practices must become widely used urgently to provide some contribution (Borrelli et al., 2020).

The increase in demand for irrigation favors the use of saline water. Salinity is the sum of all solids dissolved in the water. It may represent a constraint to irrigation since the salinity of the water is proportional to the demands of crops. If salinity increases, more water is necessary for the same amount of crop production. Although irrigation with saline waters may sustain crop production in the short term, it will inevitably lead to lower soil conditions, which is more challenging than the risk of plant osmotic stress. Accumulating salts diminishes water infiltration and progressively lowers the ability to sustain plant development. Around 10-15% of farmland worldwide faces some degree of salinization, while < 1% of irrigated land is lost to salinization each year (Madramootoo & Fyles, 2010), which may ultimately lead to desertification. Climate change contributes to faster salinization. It diminishes rainfall that counteracts salinization since rain is mostly free of salts. Further, climate change increases water evaporation and leads to greater water salinity on the soil surface.

4. Strategies to Mitigate the Effects of Climate Change

There are numerous strategies to mitigate the impact of climate change on agriculture such as land use/ management systems, crop improvement, and adapting food use or demand (Anderson et al., 2020). These strategies are not mutually exclusive but could form synergies to improve food production and security under irrigated agriculture (Figure 2). Nonetheless, the complexity of climate change effects will likely lead to several adaptation strategies tailored to each regional setting.

Traditional agriculture relies on crop monoculture (Alkorta et al., 2004). This approach to food production exacerbates the susceptibility to pathogens and plagues. Pathogens benefit from water availability, atmospheric CO2 concentrations, and temperature (Anderson et al., 2020). Therefore, climate change may favor pathogens by increasing virulence and plant susceptibility at the regional level (Hoffmann, 2017). With increasing impact of climate change, agricultural fields may interact with new pathogens with enhanced disease virulence (Anderson et al., 2020). The relatively short life cycle of pathogens in comparison to annual and perennial crops suggests faster adaptation to evolving challenging environmental conditions due to climate change (Hoffmann, 2017). As alternatives to these issues, crop diversification or rotation are examples of alternatives to the changing landscape of agriculture under climate change (Atlin et al., 2017; Degani et al., 2019).

The fact that some plants may succumb to challenging environmental conditions by climate change and others thrive suggests a genetic component to adaptation. Further, plant breeding may ultimately lead to the development of plant cultivars tolerant or less susceptible to climate change effects. Archeological evidence in

Mexico suggests that plant domestication was initiated around 5,000 BC. Several hybrid maize varieties around 800 BC grew in irrigated fields. The "green revolution" also boosted the use of genetically improved crops, alongside fertilizers and pesticides (Madramootoo & Fyles, 2010). Due to the evolving scenario of climate change and the complex nature of genetic control of stress tolerance (Anderson et al., 2020), the scientific community considers relying on cutting-edge technology (*e.g.*, genomics, gene editing) to accelerate the development of new plant cultivars tolerant to climate change (Hoffman, 2017; Anderson et al., 2020). Although the investment in breeding for plant fitness has enormous potential, alternate breeding programs to improve crop nutritional value under climate change conditions also deserve attention. Management of soil microbiome also has the potential to increase crop yields and assist in disease control (Toju et al., 2018). Recent technologies will likely contribute toward further boosts in agricultural productivity. Breeding short-season crop varieties also resulted in more efficient water usage (Madramootoo & Fyles, 2010).

Food security under climate change may rely on increased food production, altered food demand, and reduced food waste or loss (Anderson et al., 2020). Human diet composition has important social, financial, and cultural components, which also has a substantial negative effect on the environment. Shifts in the diet could assist on managing the impacts of climate change, by combining nutritional value with resource demands, and local availability, among other factors. For instance, human consumption of animal products demands the highest agricultural inputs with a greater impact on the environment. This scenario worsens by greenhouse gas production in livestock, which favors a substantial contribution to climate change itself. Therefore, diminishing the demand for animal-derived products may contribute to mitigating climate change effects on multiple levels. Despite the challenge of feeding an ever-growing human population, food waste continues to increase worldwide. The causes of food waste vary among countries, where the lack of adequate infrastructure for food supply dominates in developing countries and household practices in developed ones. Government policies for providing adequate support to food production chains and educational programs may diminish food waste or loss (Anderson et al., 2020).

5. Agroecological Systems or Traditional Knowledge to Mitigate Climate Change Effects

The consequences of unsustainable agricultural practices and climate change effects call for the adoption of transformative practices for food production. The application of practices common to agroecological systems and traditional knowledge should contribute to more sustainable agriculture with less impact on the environment and human health (Figure 2). The idea of agriculture sustainability does not preclude the use of any technology and further adapts management practices to local conditions (Pretty, 2008).

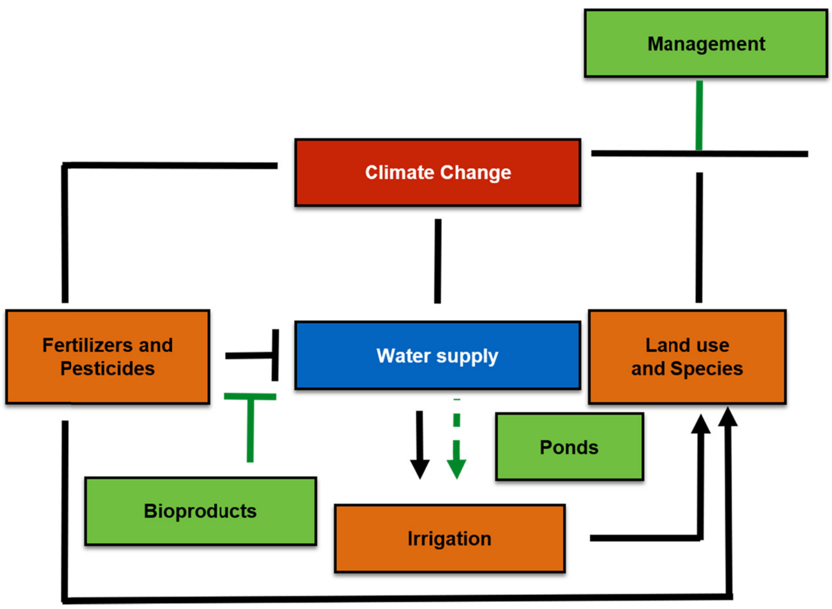

Figure 2. Contextual practices to mitigate climate change effects on irrigated agriculture

Agroecological systems hold specific characteristics or concepts that include minimizing the dependency on external inputs, resource recycling, resilience, multifunctionality, greater system complexity and integration, contextualization, equity, and nourishment (Vaarst et al., 2018). Therefore, adhering to these concepts will overcome some of the challenges posed by current agricultural practices.

Minimum external inputs reason for a more sustainable approach that is less dependent on foreign resources while more reliant on local resources such as energy supply and workers. In the context of irrigated agriculture, the application of low-energy precision irrigation methods is very appealing (Rajagopal et al., 2014; Bordovsky, 2019). Further, green manuring (perhaps with locally available plants) could lead to greater moisture content within the rooting zone and greater crop yields (Karyoti et al., 2021). Applying the resource-recycling concept, could mean more intense use of wastewater recycling for irrigation but also considering potential contamination and salinization effects (Zhang & Shen, 2019). Green manure and the residual crop can also boost soil traits to increase crop productivity (Saikia et al., 2019).

Resilience is the ability to adapt to shifting conditions. One core factor of resilience is diverse genetic resources. For instance, traditional agroecosystems maintain genetic diversity in crops (Ramankutty et al., 2018). Crop rotation and diversification are other approaches to gaining resilience (Lin, 2011; Birthal & Hazrana, 2019; Bowles et al., 2020). These alternatives give the farmer more flexibility to adjust its reliance on irrigation to crop productivity under varying environmental conditions, most notably water availability. Multifunctionality is a concept that agriculture plays other roles, such as maintaining biodiversity, preserving natural resources, and contributing to socioeconomic viability (Klein et al., 2014). These demands are also under the pressure of evolving landscapes, as described in peri-urban areas (Jampani et al., 2020).

Complexity and integration contemplate enhancing potential interactions in the agroecological system to ensure adaptive capacity to issues of seasonality, production, and crop storage (Alkorta et al., 2004; Vaarst et al., 2018; De, 2021). This could mean adopting irrigation to conditions of more sustainable use of water, thus favoring an equilibrium between productivity and natural resource allocation. Contextualization is a concept that connects with other concepts above. It demands the adaptation of agricultural practices to local conditions (Kumar, 2017), thus favoring potential resources of the place and mitigating limiting factors of the same region (Das & Ansari, 2021). Irrigation practices should adjust to such perspective, more precisely delivering homogenous amounts of water to specific crops, under specific soil, environmental, and management conditions.

Equitability favors the multi-factor nature of agroecological systems and the pivotal role of human resources in agricultural endeavors. Farmers are at the forefront of mitigating climate change effects on agriculture, albeit most of the scientific literature does not contemplate their role (Soubry et al., 2020). The engagement of farmers in mitigating climate change effects requires the adequate perception of its impact on agriculture long-term (Soubry et al., 2020), and understanding factors driving their willingness to adopt new technologies (Haden et al., 2012; Mutambara, 2016). Alternatively, farmers may also adopt practices that increase climate change effects (Houser & Stuart, 2020). Finally, the rational use of irrigation is a source of nourishment, which provides non-destructive input to the agroecological system.

Traditional knowledge comes from community, local, and rural experiences (De, 2021). In many instances, such knowledge is sustainable, cost-effective, and in agreement with agroecological system principles (De & Singh, 2017; De, 2021). For instance, the use of locally available materials (*e.g.*, stones, bamboo) to protect water sources in India (De, 2021). Further, strategies based on traditional knowledge contribute to ensuring water availability in several countries (Rivera-Ferre et al., 2016). In such a context, irrigation relies on community irrigation management, temporary dams or canals, and bamboo pipes as the low-cost infrastructure used for the rational use of water (Rivera-Ferre et al., 2016).

Irrigation ponds are another instructive example of traditional knowledge for more sustainable agriculture (López-Felices et al., 2020). Ponds have been used for centuries in the context of agriculture (Anjum et al., 2010). These structures are small and shallow ponds ranging from one to fifty thousand meters in area, with smallholder farmers as the most frequent applicants of this technology (López-Felices et al., 2020). Ponds retain rain, irrigation or from other surface water source. This simple strategy allows for relying less on rainfall and irrigation to sustain the water supply for crop development (Oweis & Hachum, 2006).

6. Perspectives on Improving Irrigated Agriculture

The mitigation of climate change effects on irrigated agriculture is a moving target, so there is no one-size-fits-all solution. Rather, it demands adaptations of mitigating practices to local conditions, which will benefit from specific (and perhaps local) agroecological approaches or traditional knowledge. The past offers numerous examples of the success and failure cases of irrigated agriculture projects. The comparison of African and Asian countries provides interesting details of how local factors come into play to implement irrigation projects and the main factors determining the output of such endeavors.

There are few examples of successful irrigation endeavors in Africa (Mutambara et al., 2016). Farmer's engagement has been limited in Africa, further complicated by insufficient maintenance of irrigation systems, and lack of long-term governmental support. Underground water use has been low in Africa, due to high costs and small aquifers (Mutambara et al., 2016). Therefore, the lack of African ability to manage water supplies ultimately jeopardizes the application of irrigation. The implementation costs of irrigated cultures differ vastly between regions and continents (Mutambara et al., 2016). Therefore, governmental policies are mandatory for supporting irrigation activities long-term directly or by favoring the participation of players from the private sector or non-profit organizations (Madramootoo & Fyles, 2010; Mutambara et al., 2016).

Over time, different irrigation methods have been implemented, however, drip irrigation is considered the most sustainable and the most widely used due to its low cost. Another irrigation system is the one that is designed automatically for crops, using low-cost technology, at the service of people, integrating an Arduino board, with humidity sensors to measure soil hydration levels and temperature sensors. To measure air humidity, so that the signal that gives way to automatic irrigation is activated or not (Guijarro-Rodríguez et al., 2018; Bringas-Burgos et al., 2020). For example, Colombia has adopted this type of system, which is powered by photovoltaic solar energy, thus allowing energy savings, and at the same time measuring analog signals in different types of crops (Guijarro-Rodríguez et al., 2018).

The success of irrigation in Asia is due to traditional management systems, farmer engagement that reduces production costs, government assistance, and rational water usage (Mutambara et al., 2016). Irrigation in Asia also benefited from the public construction of irrigation canals and the exploitation of underground water. Another hint of Asian success is the ability to adapt to transitioning conditions (Mutambara et al., 2016). Due to growing water scarcity, Asian farmers adapted irrigation practices by using underground water, water recycling, implementing adaptations to irrigation timing, adjusting cropping patterns, and focusing on the exploration of high-value crops (Barker & Molle, 2004).

7. Summary

Anthropogenic activities have generated different alterations in the environment and climate change, which have had an impact on transformations in agricultural practices to adapt to these phenomena, including the implementation of irrigated agriculture to maintain and/or improve their productivity. This practice together with the implementation of agroecological systems through local traditional knowledge offer alternatives to mitigate not only the effects of climate change in the context of agriculture at its different scales.

In addition, the implementation of mitigating practices will likely require effort from multiple fronts. Looking ahead, scientific research (Malhi et al., 2021), alongside approaches such as spatial monitoring, and computational modeling (Bonfils & Lobell, 2007; Liu et al., 2021) should be more widely used shortly. Further, the role of farmers cannot be underestimated and their engagement is paramount to adapting to new approaches (Price et al., 2014; Soubry et al., 2020). These tools will likely become instrumental in monitoring how mitigating practices contribute to sustaining crop productivity in irrigated areas under challenging conditions due to climate change.

References

Ahsan, N., Lee, D. G., Lee, S. H., Lee, K. W., Bahk, J. D., & Lee, B. H. (2007). A proteomic screen and identification of waterlogging-regulated proteins in tomato roots. *Plant and Soil, 295*, 37-51. http://doi.org/10.1007/s11104-007-9258-9

Alkorta, I., Albizu, I., Amezaga, I., Onaindia, M., Buchner, V., & Garbisu, C. (2004). Climbing a ladder: A step-by-step approach to understanding the concept of agroecosystem health. *Reviews on Environmental Health, 19*, 141-159. http://doi.org/10.1515/REVEH.2004.19.2.141

Anderson, R., Bayer, P. E., & Edwards, D. (2020). Climate change and the need for agricultural adaptation. *Current Opinion in Plant Biology, 56*, 197-202. http://doi.org/10.1016/j.pbi.2019.12.006

Anjum, S. A., Wang, L. C., Xue, L. L., Saleem, M. F., Wang, G. X., & Zou, C. M. (2010). Desertification in Pakistan: causes, impacts and management. *Journal of Food, Agriculture and Environment, 8*, 1203-1208.

Atlin, G. N., Cairns, J. E., & Das, B. (2017). Rapid breeding and varietal replacement are critical to adaptation of cropping systems in the developing world to climate change. *Global Food Security, 12*, 31-37. http://doi.org/10.1016/j.gfs.2017.01.008

Barker, R., & Molle, F. (2004). *Evolution of Irrigation in South and Southeast Asia* (Research Report, No. 5). Comprehensive Assessment of Water Management in Agriculture, Colombo, Sri Lanka. Retrieved from http://www.iwmi.cgiar.org/assessment/files/pdf/publications/ResearchReports/CARR5.pdf

Birthal, P. S., & Hazrana, J. (2019). Crop diversification and resilience of agriculture to climatic shocks: Evidence from India. *Agricultural Systems, 173*, 345-354. http://doi.org/10.1016/j.agsy.2019.03.005

Bolaños, C. S., & Betancur, V. T. (2018). Estado del arte sobre el cambio climático y las aguas subterráneas. Ejemplos en Colombia. *Revista Politécnica, 14*, 52-64. http://doi.org/https://doi.org/10.33571/rpolitec.v14n26a5

Bonfils, C., & Lobell, D. (2007). Empirical evidence for a recent slowdown in irrigation-induced cooling. *Proceedings of the National Academy of Sciences, 104*, 13582-13587. http://doi.org/10.1073/pnas.0700144104

Bordovsky, J. P. (2019). Low-energy precision application (LEPA) irrigation: A forty-year review. *Transactions of the Asabe, 62*, 1343-1353. http://doi.org/10.13031/trans.13117

Borrelli, P., Robinson, D. A., Panagos, P., Lugato, E., Yang, J. E., Alewell, C., & Ballabio, C. (2020). Land use and climate change impacts on global soil erosion by water (2015-2070). *Proceedings of the National Academy of Sciences, 117*, 21994-22001. http://doi.org/10.1073/pnas.2001403117

Bowles, T. M., Mooshammer, M., Socolar, Y., Calderón, F., Cavigelli, M. A., Culman, S. W., & Grandy, A. S. (2020). Long-term evidence shows that crop-rotation diversification increases agricultural resilience to adverse growing conditions in North America. *One Earth, 2*, 284-293. http://doi.org/10.1016/j.oneear.2020.02.007

Bringas-Burgos, B., Mendoza-Muñoz, I., Navarro-González, C., González-Ángeles, A., Jacobo-Galicia, G. (2020). Análisis de sistemas de riego por gravedad y goteo subsuperficial basada en una encuesta de muestra de conveniencia en el valle de Mexicali. *Vínculos, 5*, 13-32. http://doi.org/10.24133/vinculosespe.v5i3.1725

Cuthbert, M. O., Gleeson, T., Moosdorf, N., Befus, K. M., Schneider, A., Hartmann, J., & Lehner, B. (2019). Global patterns and dynamics of climate-groundwater interactions. *Nature Climate Change, 9*, 137-141. http://doi.org/10.1038/s41558-018-0386-4

Das, U., & Ansari, M. A. (2021). The nexus of climate change, sustainable agriculture and farm livelihood: Contextualizing climate smart agriculture. *Climate Research, 84*, 23-40. http://doi.org/10.3354/cr01648

De, L. C., & Singh, D. R. (2017). Natural resources in North East region of India. *International Journal of Agricultural Science and Research, 7*, 51-66. https://doi.org/10.24247/ijasroct20178

De, L. C. (2021). Traditional knowledge practices of North East India for sustainable agriculture. *Journal of Pharmacogenosy and Phytochemistry, 10*, 549-556.

Degani, E., Leigh, S. G., Barber, H. M., Jones, H. E., Lukac, M., Sutton, P., & Potts, S. G. (2019). Crop rotations in a climate change scenario: Short-term effects of crop diversity on resilience and ecosystem service provision under drought. *Agriculture, Ecosystems & Environment, 285*, 106625. http://doi.org/10.1016/j.agee.2019.106625

Fischer, G., Shah, M., N. Tubiello, F., & Van, V. H. (2005). Socio-economic and climate change impacts on agriculture: an integrated assessment, 1990-2080. *Philosophical Transactions of the Royal Society B: Biological Sciences, 360*, 2067-2083. http://doi.org/10.1098/rstb.2005.1744

Foley, J. A., DeFries, R., Asner, G. P., Barford, C., Bonan, G., Carpenter, S. R., & Snyder, P. K. (2005). Global consequences of land use. *Science, 309*, 570-574. http://doi.org/10.1126/science.1111772

Fuller, D. Q., & Stevens, C. J. (2019). Between domestication and civilization: the role of agriculture and arboriculture in the emergence of the first urban societies. *Vegetation History and Archaeobotany, 28*, 263-282. http://doi.org/10.1007/s00334-019-00727-4

Guijarro-Rodríguez, A. A., Cevallos-Torres, L. J., Preciado-Maila, D. K., & Zambrano, M. B. N. (2018). Sistema de riego automatizado con Arduino. *Revista Espacios, 39*, 27-39.

Gulhati, N. D., & Smith, W. C. (1967). Irrigated agriculture and historical review. *Irrigation of Agricultural lands* (Agronomy 11, pp. 3-11). American Society of Agronomy, Madison, USA. Http://doi.org/10.2134/agronmogr11.c1

Goudriaan, J., & Zadoks, J. C. (1995). Global climate change: modelling the potential responses of agro-ecosystems with special reference to crop protection. *Environmental Pollution, 87*, 215-224. https://doi.org/10.1016/0269-7491(94)P2609-D

Haden, V. R., Niles, M. T., Lubell, M., Perlman, J., & Jackson, L. E. (2012). Global and local concerns: what attitudes and beliefs motivate farmers to mitigate and adapt to climate change? *PloS One, 7*, e52882. http://doi.org/10.1371/journal.pone.0052882

Hoffmann, A. A. (2017). Rapid adaptation of invertebrate pests to climatic stress? *Current Opinion in Insect Science, 21*, 7-13. http://doi.org/10.1016/j.cois.2017.04.009

Houser, M., & Stuart, D. (2020). An accelerating treadmill and an overlooked contradiction in industrial agriculture: Climate change and nitrogen fertilizer. *Journal of Agrarian Change, 20*, 215-237. http://doi.org/10.1111/joac.12341

Jampani, M., Amerasinghe, P., Liedl, R., Locher-Krause, K., & Hülsmann, S. (2020). Multi-functionality and land use dynamics in a peri-urban environment influenced by wastewater irrigation. *Sustainable Cities and Society, 62*, 102305. http://doi.org/10.1016/j.scs.2020.102305

Karyoti, A., Giannoulis, K. D., Bartzialis, D., Hatzigiannakis, E., Skoufogianni, E., & Danalatos, N. G. (2021). Green Manuring for Low-input Irrigated Maize Cultivation as an Energy Crop in Mediterranean Climates. *International Journal of Plant Production, 15*, 563-575. http://doi.org/10.1007/s42106-021-00165-1

Klein Goldewijk, K., & Ramankutty, N. (2004). Land cover change over the last three centuries due to human activities: The availability of new global data sets. *GeoJournal, 61*, 335-344. https://doi.org/10.1007/s10708-004-5050-z

Klein, T., Holzkämper, A., Calanca, P., & Fuhrer, J. (2014). Adaptation options under climate change for multifunctional agriculture: a simulation study for western Switzerland. *Regional Environmental Change, 14*, 167-184. http://doi.org/10.1007/s10113-013-0470-2

Kumar, S. N. (2017). Improving crop adaptations to climate change: Contextualizing the strategy. *Abiotic Stress Management for Resilient Agriculture* (pp. 277-298). Springer, Singapore. https://doi.org/10.1007/978-981-10-5744-1_12

Leisner, C. P. (2020). Climate change impacts on food security-focus on perennial cropping systems and nutritional value. *Plant Science, 293*, 110412. http://doi.org/10.1016/j.plantsci.2020.110412

Lin, B. B. (2011). Resilience in agriculture through crop diversification: adaptive management for environmental change. *BioScience, 61*, 183-193. https://doi.org/10.1525/bio.2011.61.3.4

Liu, Z., Yang, X., Hubbard, K. G., & Lin, X. (2012). Maize potential yields and yield gaps in the changing climate of northeast China. *Global Change Biology, 18*, 3441-3454. http://doi.org/10.1111/j.1365-2486.2012.02774.x

Liu, X., Cao, A., Yan, D., Ouyang, C., Wang, Q., & Li, Y. (2021a). Overview of mechanisms and uses of biopesticides. *International Journal of Pest Management, 67*, 65-72. Http://doi.org/10.1080/09670874.2019.1664789

Liu, K., Harrison, M. T., Archontoulis, S. V., Huth, N., Yang, R., Li Liu, D., & Zhou, M. (2021b). Climate change shifts forward flowering and reduces crop waterlogging stress. *Environmental Research Letters, 16*, 094017. http://doi.org/10.1088/1748-9326/ac1b5a

López-Felices, B., Aznar-Sánchez, J. A., Velasco-Muñoz, J. F., & Piquer-Rodríguez, M. (2020). Contribution of irrigation ponds to the sustainability of agriculture. A review of worldwide research. *Sustainability, 12*, 1-18. http://doi.org/10.3390/agronomy10101499

Lu, S., Bai, X., Li, W., & Wang, N. (2019). Impacts of climate change on water resources and grain production. *Technological Forecasting and Social Change, 143*, 76-84. http://doi.org/10.1016/j.techfore.2019.01.015

Lucero-Vega, G., Troyo-Diéguez, E., Murillo-Amador, B., Nieto-Garibay, A., Ruiz-Espinoza, H. F., Beltrán-Morañes, A. F., & Zamora-Salgado, S. (2017). Diseño de un sistema de riego subterráneo para abatir la evaporación en suelo desnudo comparado con dos métodos convencionales. *Agrociencia, 51*, 487-505.

Madramootoo, C. A., & Fyles, H. (2010). Irrigation in the context of today's global food crisis. *Irrigation and Drainage: The Journal of the International Commission on Irrigation and Drainage, 59*, 40-52. http://doi.org/10.1002/ird.555

Maisels, C. K. (2003). *The emergence of civilization: From hunting and gathering to agriculture, cities, and the state of the near east*. Routledge.

Montgomery, D. R. (2007). Soil erosion and agricultural sustainability. *Proceedings of the National Academy of Sciences, 104*, 13268-13272. http://doi.org/10.1073pnas.0611508104

Mutambara, S. (2016). Smallholder irrigation farmers' financial exclusion in Zimbabwe: A resilience threat. *International Journal of Agricultural Policy and Research, 4*, 256-270. http://doi.org/10.15739/IJAPR.16.027

Nearing, M. A., Pruski, F. F., & O'Neal, M. R. (2004). Expected climate change impacts on soil erosion rates: a review. *Journal of Soil and Water Conservation, 59*, 43-50.

FAO (Organización de las Naciones Unidas para la Alimentación y la Agricultura). (2020). *World Food and Agriculture—Statistical Yearbook*. http://doi.org/10.4060/cb1329en

O'Neal, M. R., Nearing, M. A., Vining, R. C., Southworth, J., & Pfeifer, R. A. (2005). Climate change impacts on soil erosion in Midwest United States with changes in crop management. *Catena, 61*, 165-184. http://doi.org/10.1016/j.catena.2005.03.003

Oweis, T., & Hachum, A. (2006). Water harvesting and supplemental irrigation for improved water productivity of dry farming systems in West Asia and North Africa. *Agricultural Water Management, 80*, 57-73. http://doi.org/10.1016/j.agwat.2005.07.004

Pacifici, M., Foden, W. B., Visconti, P., Watson, J. E., Butchart, S. H., Kovacs, K. M., & Rondinini, C. (2015). Assessing species vulnerability to climate change. *Nature Climate Change, 5*, 215-224. http://doi.org/10.1038/nclimate2448

Pedersen, O., Colmer, T. D., & Sand-Jensen, K. (2013). Underwater photosynthesis of submerged plants-recent advances and methods. *Frontiers in Plant Science, 4*, 140. http://doi.org/10.3389/fpls.2013.00140

Ploschuk, R. A., Miralles, D. J., Colmer, T. D., & Striker, G. G. (2020). Waterlogging differentially affects yield and its components in wheat, barley, rapeseed and field pea depending on the timing of occurrence. *Journal of Agronomy and Crop Science, 206*, 363-375. http://doi.org/10.1111/jac.12396

Pretty, J. (2008). Agricultural sustainability: Concepts, principles and evidence. *Philosophical Transactions of the Royal Society B: Biological Sciences, 363*, 447-465. http://doi.org/10.1098/rstb.2007.2163

Price, J. C., Walker, I. A., & Boschetti, F. (2014). Measuring cultural values and beliefs about environment to identify their role in climate change responses. *Journal of Environmental Psychology, 37*, 8-20. http://doi.org/10.1016/j.jenvp.2013.10.001

Quinton, J. N., Govers, G., Van Oost, K., & Bardgett, R. D. (2010). The impact of agricultural soil erosion on biogeochemical cycling. *Nature Geoscience, 3*, 311-314. http://doi.org/10.1038/ngeo838

Rajagopal, G., Lodd, V. M., Vignesh, A., Rajesh, R., & Vijayaraghavan, V. (2014). *Low cost cloud based intelligent farm automation system using Bluetooth low energy* (pp. 127-132). 2014 IEEE Region 10 Humanitarian Technology Conference (R10 HTC), IEEE. https://doi.org/10.1109/R10-HTC.2014.7026324

Ramankutty, N., Mehrabi, Z., Waha, K., Jarvis, L., Kremen, C., Herrero, M., & Rieseberg, L. H. (2018). Trends in global agricultural land use: Implications for environmental health and food security. *Annual Review of Plant Biology, 69*, 789-815. http://doi.org/10.1146/annurev-arplant-042817-040256

Rivera-Ferre, M. G., Di Masso, M., Vara, I., Cuellar, M., Calle, A., Mailhos, M., & Gallar, D. (2016). Local agriculture traditional knowledge to ensure food availability in a changing climate: Revisiting water management practices in the Indo-Gangetic Plains. *Agroecology and Sustainable Food Systems, 40*, 965-987. http://doi.org/10.1080/21683565.2016.1215368

Rosales, M. V., Francisco, R. A., Casanova, P. L., Fraire, C. S., Flota, B. C., & Galicia, G. F. (2020). Percepción de citricultores ante el efecto del cambio climático en Campeche. *Revista Mexicana de Ciencias Agrícolas, 11*, 727-740. http://doi.org/https://doi.org/10.29312/remexca.v11i4.1898

Saikia, R., Sharma, S., Thind, H. S., & Sidhu, H. S. (2019). Temporal changes in biochemical indicators of soil quality in response to tillage, crop residue and green manure management in a rice-wheat system. *Ecological Indicators, 103*, 383-394. http://doi.org/10.1016/j.ecolind.2019.04.035

Shaw, R. E., Meyer, W. S., McNeill, A., & Tyerman, S. D. (2013). Waterlogging in Australian agricultural landscapes: a review of plant responses and crop models. *Crop and Pasture Science, 64*, 549-562. http://doi.org/10.1071/CP13080

Soubry, B., Sherren, K., & Thornton, T. F. (2020). Are we taking farmers seriously? A review of the literature on farmer perceptions and climate change, 2007-2018. *Journal of Rural Studies, 74*, 210-222. http://doi.org/ 10.1016/j.jrurstud.2019.09.005

Taylor, R. G., Scanlon, B., Döll, P., Rodell, M., Van Beek, R., Wada, Y., & Treidel, H. (2013). Ground water and climate change. *Nature Climate Change, 3*, 322-329. http://doi.org/10.1038/nclimate1744

Toju, H., Peay, K. G., Yamamichi, M., Narisawa, K., Hiruma, K., Naito, K., & Kiers, E. T. (2018). Core microbiomes for sustainable agroecosystems. *Nature Plants, 4*, 247-257. http://doi.org/10.1038/s41477-018-0139-4

Tripathi, A., Tripathi, D. K., Chauhan, D. K., Kumar, N., & Singh, G. S. (2016). Paradigms of climate change impacts on some major food sources of the world: A review on current knowledge and future prospects. *Agriculture, ecosystems & Environment, 216*, 356-373. http://doi.org/10.1016/j.agee.2015.09.034

Vaarst, M., Escudero, A. G., Chappell, M. J., Brinkley, C., Nijbroek, R., Arraes, N. A., & Halberg, N. (2018). Exploring the concept of agroecological food systems in a city-region context. *Agroecology and Sustainable Food Systems, 42*, 686-711. http://doi.org/10.1080/21683565.2017.1365321

Voesenek, L. A., & Bailey-Serres, J. (2015). Flood adaptive traits and processes: An overview. *New Phytologist, 206*, 57-73. http://doi.org/10.1111/nph.13209

Weisdorf, J. L. (2005). From foraging to farming: Explaining the Neolithic Revolution. *Journal of Economic Surveys, 19*, 561-586. https://doi.org/10.1111/j.0950-0804.2005.00259.x

Xuewen, X., Huihui, W., Xiaohua, Q., Qiang, X., & Xuehao, C. (2014). Waterlogging-induced increase in fermentation and related gene expression in the root of cucumber (Cucumis sativus L.). *Scientia Horticulturae, 179*, 388-395. http://doi.org/10.1016/j.scienta.2014.10.001

Zhang, Y., & Shen, Y. (2019). Wastewater irrigation: Past, present, and future. *Wiley Interdisciplinary Reviews*: *Water, 6*, e1234. http://doi.org/10.1002/wat2.1234

Zhou, W., Chen, F., Meng, Y., Chandrasekaran, U., Luo, X., Yang, W., & Shu, K. (2020). Plant waterlogging/flooding stress responses: From seed germination to maturation. *Plant Physiology and Biochemistry, 148*, 228-236. http://doi.org/10.1016/j.plaphy.2020.01.020