



Editorial

Water Management for Sustainable Food Production

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Abstract: The agricultural community has a challenge of increasing food production by more than 70% to meet demand from the global population increase by the mid-21st century. Sustainable food production involves the sustained availability of resources, such as water and energy, to agriculture. The key challenges to sustainable food production are population increase, increasing demands for food, climate change, and climate variability, decreasing per capita land and water resources. To discuss more details on (a) the challenges for sustainable food production and (b) mitigation options available, a special issue on “Water Management for Sustainable Food Production” was assembled. The special issue focused on issues such as irrigation using brackish water, virtual water trade, allocation of water resources, consequences of excess precipitation on crop yields, strategies to increase water productivity, rainwater harvesting, irrigation water management, deficit irrigation, and fertilization, environmental and socio-economic impacts, and irrigation water quality. Articles covered several water-related issues across the U.S., Asia, Middle-East, Africa, and Pakistan for sustainable food production. The articles in the special issue highlight the substantial impacts on agricultural production, water availability, and water quality in the face of increasing demands for food and energy.

Keywords: deficit irrigation; excess precipitation; irrigation water quality; virtual water; water productivity; brackish groundwater; rainwater harvesting; socio-economic impacts

1. Introduction

Sustainable food production involves the sustained availability of resources, such as water and energy, to agriculture. The key challenges to sustainable food production are population increase, availability of resources at the right time and place, threats posed by climate variability and extremes to land and water which are often exacerbated by other biophysical limits such as declining per-capita land and water scarcity, as well as rising demand for agricultural products [1,2]. The emerging consensus is that the world likely will exceed nine billion people by 2050, requiring 70%, 80%, and 55%, more food, water, and energy, respectively [3–5]. Increasing agricultural productivity and developing sustainable water management techniques are needed to feed the ever-increasing population [1,6]. Projected climate change is expected to affect crop and livestock production substantially, and water availability and quality. Climate change and variability, as well as extremes, including floods and droughts, further aggravate the challenges to sustainable food production. Innovative strategies are needed to mitigate these negative impacts while meeting the increasing demands in a sustainable manner [7].

Efficient and smart use of resources, and the adoption of less water-intensive crop production systems, are the present requirements to achieve sustainable food production. Advanced crop production methods such as precision farming, access to low-cost data, advancement in electronic gadgets, and smart instruments have opened up plenty of opportunities for agricultural producers

to gear up towards sustainable food production. However, the knowledge of managing water in agriculture with existing technology has not reached many parts of the world. Therefore, this special issue is developed to bring out the knowledge on water management towards sustainable food production in an open-access platform.

This Special Issue aims to bring forth the challenges and discuss the mitigation options on the availability of water to both rain-fed and irrigated agricultural production (including animal production) to sustain food production at local, regional, national, and global scales.

In particular, the Special Issue focused on:

1. Use of Smart technology (electronic gadgets, low-cost data sources, local technology) to manage water to obtain more crop per drop.
2. Agricultural production under shrinking land and water resources.
3. Availability of water to agricultural production under historical past and projected future climate change (including floods, droughts, and extremes of precipitation and temperature).
4. Sustaining agricultural production under population increase with existing water resources.

In this introductory article, we highlight the major findings from papers published in this collection. A summary of the articles in the special issue is presented in Table 1. This Edited Collection, “Water Management for Sustainable Food Production,” includes fifteen articles (thirteen are research articles, two review articles). These studies cover a wide range of topics related to water management for various crop production systems in different parts of the world.

Table 1. Summary of articles included in the Special Issue on Water Management for Sustainable Food Production.

Authors	Citation	Food Production Systems	Water Management	Focus Region
Katuri et al., 2019 [8]	<i>Water</i> 2019, 11(12), 2556 [8]	Olive	Drip irrigation systems using brackish groundwater	Israel
Ali et al., 2019 [9]	<i>Water</i> 2019, 11(11), 2259 [9]	15 major agricultural commodities	Virtual water trade to analyze water use sustainability	Pakistan
Gedefaw et al., 2019 [10]	<i>Water</i> 2019, 11(10), 1966 [10]	Rainfed agriculture (specific crop N/A)	Allocate water supplies to maximize economic benefits	Ethiopia
Sharma et al., 2019 [11]	<i>Water</i> 2019, 11(9), 1920 [11]	Sorghum	Consequences of Excess precipitation on crop yields	Texas, USA
Lampayan et al., 2019 [12]	<i>Water</i> 2019, 11(9), 1816 [12]	Rice	Crop management strategies to increase water productivity and decrease irrigation	Lao
Kaioglu et al., 2019 [13]	<i>Water</i> 2019, 11(8), 1730 [13]	Canola	Crop management techniques and water productivity	North Dakota, USA
Silungwe et al., 2019 [14]	<i>Water</i> 2019, 11(3), 578 [14]	Pearl Millet Yield	Rainwater harvesting techniques	Central Tanzania
Gadédjisso-Toussou et al., 2019 [15]	<i>Water</i> 2018, 10(12), 1803 [15]	Maize	Five irrigation management techniques	West Africa
Fan et al., 2019 [16]	<i>Water</i> 2018, 10(11), 1637 [16]	Studied 17 crops Focus: corn, soybean	Farmers’ decision making, economics, irrigation water use efficiency	48 states in the USA
Materu et al., 2019 [17]	<i>Water</i> 2018, 10(8), 1018 [17]	Rice	Three irrigation management alternatives	Tanzania
Trifnov et al., 2019 [18]	<i>Water</i> 2018, 10(8), 970 [18]	Potato	Reduced water (drip irrigation) and fertilization	Areal desert, Israel
Ket et al., 2019 [19]	<i>Water</i> 2018, 10(5), 666 [19]	Lettuce	Water-saving irrigation strategies	Kampong Chhnang, Cambodia
Sekvi-Annan et al., 2019 [20]	<i>Water</i> 2018, 10(5), 624 [20]	Tomato-Maize Rotation-System	Reservoir-Based Irrigation Scheme	Ghana
Velasco-Muñoz et al., 2019 [21]	<i>Water</i> 2019, 11(9), 1758 [21]	Agricultural Production Systems	Environmental, economic, social impacts	Ghana
Malakar et al., 2019 [22]	<i>Water</i> 2019, 11(7), 1482 [22]	Food crops	Irrigation water quality impacts on crop/soil: Source contaminants	Ghana

2. Content of the Special Issue

Two review articles in the special collection bring out the global perspective on irrigation, which is considered the highest consumptive use of freshwater [21,22]. Velasco-Muñoz et al. (2019) [21] reviewed 713 articles on sustainable irrigation in agriculture over the last twenty years (1999–2018) through a bibliometric analysis (quantitatively) and a systematic review based on keyword analysis (qualitatively). Their results show the study of sustainable irrigation has grown in recent years, which is higher than that of general research in irrigation. The study observed that the environmental dimension dominates far more than the social or economic perspectives in the research of sustainable irrigation. Substantial differences in specific approaches and preferred research topics varied with countries. The review brought out the need for integrating environmental, social, and economic dimensions in sustainable irrigation, and aimed to communicate the results of the research to society, as well as to provide greater knowledge of the environmental impacts of irrigation-related practices on different levels (plot, district, basin, region). The second review article [22] in this special collection addressed some of the environmental impacts of irrigation water quality from multiple sources (conventional sources like surface or groundwater, or nonconventional sources like reclaimed water) [22]. The study highlights the vulnerability of crop and soil quality, as well as the complexities of the composition of irrigation water to various emerging contaminants from various water sources. They focused on contaminants such as organic pollutants (e.g., pharmaceuticals, antibiotics, steroids, agrochemicals, cyanotoxins, and mycotoxins); biological contaminants such as bacteria, viruses, and antibiotic resistance, as well as inorganic contaminants such as geogenic source and nanomaterials. The study brought out the need for establishing regulations and clear guidelines for irrigation water quality to ensure healthy food production for human consumption. They emphasized the need to question the existing recommendations of contaminants when higher than recommended concentrations were bio-accumulated in crops. This understanding will help ensure adequate crop production to meet increased demand as well as to maintain proper food and soil quality.

Optimal allocation of water resources is important in basins facing water scarcity due to the increasing demands caused by population growth, urbanization, industrialization and agricultural intensification, and poor water resources management. The impacts due to these demands can have important implications in many developing countries. Three studies have demonstrated improved irrigation management strategies in Africa and Asia. These studies focus on increasing variability in rainfall and overcome deficits in current irrigation schemes. Gedefaw et al.'s (2019) [10] study formulated the water allocation networks under an irrigation expansion and climate change scenario using the calibrated water evaluation and planning (WEAP) model for the Awash River Basin, Ethiopia, facing water scarcity. In that study, water demands, water shortages, and supply alternatives were analyzed using three scenarios, namely: the reference scenario (1981–2016), the medium-term development (2017–2030), and the long-term development (2031–2050) as well as an economic parameter to maximize the economic benefits of water allocation. Their results showed that future water consumption would greatly increase in the Awash River Basin. Their results also highlight the requirement of water-saving measures to prevent future water shortages. Rice is a major food crop for more than half of the global population, with more than 90% of global rice production and consumption occurring in Asia. Efficient water use in rice production is a prerequisite to sustaining the world's food security. The objective of Lampayan et al.'s (2019) [12] study of rice production systems is to test their hypothesis that a delayed transplanting strategy reduces irrigation requirements and increases irrigation water productivity. They tested the hypothesis using a field experiment conducted in two wet seasons in Lao People's Democratic Republic by evaluating the interactive effects of seedling age, seedling density, and variety on post-transplanted rice crop development (e.g., tillering propensity), grain yield, and water productivity. Materu et al. (2019) [17] compared three variants of irrigation management alternatives (system of rice intensification (SRI)) using the conventional, continuously flooding system in Tanzania experimentally for both wet and dry seasons. SRI is a new production practice, which is a combination of the agronomic practices adopted by many farmers in Asia and Sub-Saharan Africa. The study observed that SRI resulted in water saving, an increased rice yield, and improved the economic productivity of water.

Three studies have used multiple water sources (e.g., reservoir-based, groundwater-based, brackish irrigation) to research improved irrigation management strategies in multiple crops (e.g., tomato, maize, canola, and olive) in the USA, Africa, and Asia. Sekyi-Annan et al.'s (2019) [20] study aimed to improve the traditional dry season irrigation practices in reservoir-based irrigation schemes for the tomato–maize rotation system in Ghana (Upper East region), and assessed the potential for introducing supplemental irrigation in the rainy season as an adaptation to climate change using the AquaCrop model under different climate scenarios. The improved irrigation schedule for dry season tomato cultivation resulted in water-saving (130–1325 mm) compared to traditional irrigation practices, and an increase in tomato yield (4–14%). Maize would require 107–126 mm of water in periods of low rainfall and frequent dry spells, and 88–105 mm in periods of high rainfall and rare dry spells. These water management techniques could make year-round irrigated crop production feasible, using water saved during dry season tomato cultivation for supplemental irrigation of maize in the rainy season. The main scope of Kaioglu et al.'s (2019) [13] study was to determine an optimum shallow groundwater depth to achieve a high yield, growth, and water use in canola plants using lysimetric experiments in greenhouse conditions in Fargo, North Dakota, USA. Canola plant characteristics (e.g., height, water use, total biomass and grain yield water use efficiency, root mass, root–shoot ratio, and harvesting results (total biomass, pod, and seed weight) were determined and compared for four different water table scenarios. The results suggested that the canola plant characteristics were affected by different water table levels and showed inverse linear relationships. The decrease in yields in olive orchards and replacing olive trees due to unprofitability in orchards irrigated with brackish irrigation water in the central Negev Desert, Israel, motivated Katuri et al.'s (2019) [9] study. The results of this study demonstrate that, following twenty years of irrigation with brackish irrigation water, salinization and sodification took place in the soil profile (0–60 cm, the active root zone of the olive trees). This study fills the knowledge gap regarding the spatial distribution of salinity and sodicity in long-term, sub-surface, drip-irrigated soils with brackish irrigation water. They concluded that, in the long term, utilizing marginal irrigation water sources, such as brackish water, may be fundamentally unsustainable, particularly in arid lands where precipitation is too low to leach the accumulated salts from the active root zone. The benefits of water-saving due to drip irrigation are masked by soil salinization and sodification. Reclamation of these soils with gypsum, for example, is essential. Any alternative practices, such as replacing olive trees and the further introduction of plants with even higher salinity tolerance (e.g., jojoba) in this region, will intensify the salt buildup without leaving any option for soil reclamation in the future.

Two studies addressed the availability of water to agricultural production under the historical past and projected future climate change. By documenting the relationships between reductions in rainfed crop yield and excess precipitation, Sharma et al. (2019) [11] address an existing knowledge gap. They used the historical crop yield data for Texas by county for grain sorghum from 1973 to 2000 and the corresponding daily precipitation data from weather stations within the counties, estimating the total precipitation of the growing season and the maximum four-day precipitation. Using the two parameters as independent variables, and the crop yield of sorghum as the dependent variable, they established graphical and mathematical relationships between excess precipitation and decreases in crop yields. Their results show a decrease in rainfed sorghum yields in Texas in the range of 18% and 38% due to excess precipitation. In another part of the world, Silungwe et al. (2019) [14] attempted to understand the rainfed pearl millet yield variability due to variations in seasonal rainfall in a 1500 ha area of a semiarid region in central Tanzania with and without rainwater harvesting management practice (flat and tied ridge). Rainfall data were collected from 38 rain gauge stations from November 2016 to May 2018, which includes two growing seasons. Yield data from plots near these locations were collected for both the practices (20 for the tied ridge, 18 for flat). The yield data showed the correlation with both the rainfall amounts and the number of events in a season. The use of tied ridges (an infield rainwater harvesting system) increased the pearl millet yield significantly.

Currently, the production of crops poses a greater challenge in managing effective inputs (e.g., water irrigation and fertilization) due to their sensitivity to water shortage and increasing costs. Deficit irrigation and fertilization are practices whereby a crop is irrigated and fertilized with an amount below the full requirement for optimal plant growth, thereby saving inputs and minimizing the economic impact on the harvest. Three studies have addressed this for vegetables (e.g., lettuce, potato) and cereal (e.g., maize) in different parts of the world (e.g., Cambodia, Israel, West Africa). The main objective of Ket et al.'s (2019) [19] study was to improve the water productivity of lettuce by assessing the impact of multiple water-saving scenarios (full, deficit irrigation) by developing the crop model, AquaCrop, for lettuce (currently not available in catalog) and calibrating it with observations from field experiments for Cambodia. The results suggested that a deficit irrigation strategy can save 20–60% of water compared to full irrigation scenarios. Potatoes are a high-value vegetable crop with a shallow, inefficient root system and high fertilizer rate requirements with a high risk of leaching below the root zone when grown often in sandy soils. Trifonov et al. (2019) [18] attempted to save water and fertilizer with reduced nutrient leaching in potato production. Their objective was to optimize potato growth under a low discharge drip irrigation (40%, 60%, 80%, and 100%) and fertigation (0%, 50%, and 100%) doses in Arava Desert, Israel. They used field experiments during the 2014–2015 time period. They found that water productivity was affected by water dose and nitrogen level with an 80% (438.6 mm) irrigation dose, and a 50% (50 mg N L⁻¹) fertigation dose showing optimal potato yield (about 40 ton ha⁻¹) without qualitative changes in the potato tuber. In another study, Gadédjisso-Tossou et al. (2019) [15] investigated alternative irrigation strategies in the dry savannah area of Togo, in the West African region, for a maize crop. They characterized the climate of a water-scarce region and evaluated five irrigation management strategies for combinations of no irrigation, conventional and supplemental irrigation, limited and full supply. They used the OCCASION framework (weather generator-LARS-WG, AquaCrop model, optimal irrigation scheduling algorithm) for their research. They observed (a) satisfactory performance of the LARS Weather Generator in predicting the climate of northern Togo, and (b) irrigation practice (0 to 600 mm) in agriculture lowered crop yield variability as well as crop failure.

Two studies provide additional perspectives on sustainable water use practices using multilevel models and virtual water trade assessments. Using multilevel linear regression models (MLMs), Fan et al.'s (2019) [16] study analyzed the effects of multiple factors on farmers' decision making and economical irrigation water use efficiency (EIWUE) in a multi-crop production system. The study was conducted across five regions, encompassing 48 states in the USA (Western, Plains, Midwestern, Southern, and Atlantic states) with different cropping patterns and climatic conditions. Originally, multiple factors (e.g., water sources, input costs, farming area, land characteristics, adoption of various irrigation systems, climate perceptions) at multiple levels (farm, state, regional) were identified from multiple sources (e.g., review, survey, observation) for 17 crops. However, the results in the paper focused on water source (surface, groundwater) cost and water use, as well as the adoption of pressure irrigation systems, adoption of enhanced irrigation systems, higher temperatures, and precipitation on corn and soybean yield and water use. This study could help farmers and policymakers adapt to potential climate risks, better manage the irrigation water application, and achieve the sustainable use of limited water resources. Their results show higher costs of surface water are not effective in reducing water use, while groundwater costs show a positive association with water use on both corn and soybean farms. In the second study of this category, the research by Ali et al. (2019) [9] on virtual water trade is one of the first studies to concentrate on a water-stressed, net virtual, water-exporting country (Pakistan), while most of the existing country-level studies on the virtual water trade focused on net virtual water importers, which are usually water-scarce countries as well. This paper assessed the trade and savings/losses of blue and green virtual water through 15 agricultural commodities, over the period of 1990–2016 and in 2030. The results of the study show that, in most of the studied commodities, blue VW is the major component in total water use. Pakistan has been a net exporter of blue VW, mostly through rice export to Asian and African countries. In terms of green VW, Pakistan

has been a net importer (marginally), mainly through the import of palm oil from Indonesia and Malaysia. In the future (2030), both Pakistan's domestic savings of green and losses of virtual blue water will increase by more than 200%. Their results also suggest that Pakistan has been exporting more expensive (with high opportunity cost) blue VW through its agricultural trade to the rest of the world. However, there are opportunities for improving the water use efficiency (in the export-oriented crops) and adjustment in its export portfolio of agricultural commodities by promoting the export of commodities with higher value and lower water use intensity.

3. Conclusions

This special issue was organized to initiate an interdisciplinary dialogue with stakeholder groups about mitigation and adaptation strategies for sustainable agricultural production in the face of increasing demands due to population growth, urbanization, industrialization and agricultural intensification, and inadequate water resources management. Given the scope and extent of the impacts from these increasing demands, variety in crop production systems, water sources, climate variability, as well as changes in crop production systems, differences in water resources, and ecosystem health, there is a need to form global partnerships for developing sustainable agricultural production strategies. For example, developing holistic strategies for adaptation and mitigation (e.g., improving irrigation efficiency, virtual water assessment) for sustaining crop production during resource-scarce conditions. This Special Collection highlights the fact that agricultural production, water availability, and water quality are going to be substantially impacted by increasing demands in food, energy, and water sectors. There are technological options available to mitigate the adverse impacts of climate change, but adaptation strategies will require rethinking agricultural management practices to maintain crop and livestock production while protecting environmental quality.

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