Scientific Research Publishing

Computational Water, Energy, and Environmental Engineering, 2021, 10, 18-35
https://www.scirp.org/journal/cweee
ISSN Online: 2168-1570
ISSN Print: 2168-1562

Investigation of the Relationship among Water and Crop Production under Bounded Irrigation Conditions

Tawheed Mohammed Elheesin Shareef[1,2], Zhongming Ma[1*], Juan Chen[3], Xiaoxia Niu[3]

[1]Gansu Academy of Agricultural Sciences, Lanzhou, China
[2]Department of Agriculture Engineering, Faculty of Agriculture, University of Khartoum, Khartoum, Sudan
[3]Institute of Economic Crops and Beer Materials, Gansu Academy of Agricultural Sciences, Lanzhou, China
Email: *mazhming@163.com

How to cite this paper: Shareef, T.M.E., Ma, Z.M., Chen, J. and Niu, X.X. (2021) Investigation of the Relationship among Water and Crop Production under Bounded Irrigation Conditions. *Computational Water, Energy, and Environmental Engineering*, **10**, 18-35.
https://doi.org/10.4236/cweee.2021.101002

Received: November 11, 2020
Accepted: January 4, 2021
Published: January 7, 2021

Abstract

Water scarcity is relative and variable concept that can occur at any level of supply and demand. It is also a social construct, which is linked to the intervention in the water cycle and changes over time as a result of natural hydrological change. It is more severe when water acts as a backbone in economic policies, planning and management methods. Water scarcity can be expected to increase with most forms of economic development, but, if properly identified, many of its causes can be expected and avoided or mitigated. However, the limited irrigation management is considered a very important issue in the agricultural scope. Therefore, in this study, the relationship between water, crop production, photosynthesis, crop transpiration, crop growth, crop yields and water use efficiency have been discussed under limited irrigation conditions. However, the crops have some ability to adapt and resist against limited irrigation. Hence, under high temperate conditions, this is a shortage of water and photosynthesis is decreased with a pore (stoma) restraining. At the same time, the evapotranspiration reaches to the utmost value and the water use efficiency rises because of optimal monitoring of leaf pore (stoma). Therefore, the modality which is the reduction of the risks and improving industrial control in incomplete irrigation are the chief constraints of providing irrigation water in the future, which leads to increased crop production and ultimately providing a provision of food security.

Keywords

Freshwater Consumption, Insufficient Irrigation, Water Use Efficiency, Yield Formation

1. Introduction

About 70% of global freshwater consumption is used in agricultural sector, whereas water use efficiency (WUE) in many countries is less than 50% [1] [2]. Therefore, the nuclear and theoretical techniques provide data on the use of water, including losses due to the evaporation from soil, which are helpful for the determination of optimal irrigation dates and improve water use efficiency [3]. According to the food and agriculture organization (FAO) of the United Nations, the global water requirements for agriculture will increase 50% by 2050 [4] to meet the increased demand of food with the population growth (amounts to around 83 million annually) [5]. It is predicted that the total population will be 8.6 billion by mid-2030, 9.8 billion by mid-2050 and 11.2 billion by 2100 [6]. On the other hand, due to improper management, indiscriminate use and climate change the world is witnessing fresh water scarcity.

Water scarcity and quality concerns are posing serious problems to food security and future environmental sustainability, in many parts of the world [7] [8]. Therefore, addressing of these issues requires improved land and water management for the optimization of agricultural water management practices, thereby supporting the intensification of crop production and conservation of natural resources. Furthermore, fresh water scarcity is a global issue, but the situation is getting worse especially in dry areas of the world where a little water must be used effectively for the maximized benefits [9]. Therefore, it is essential to use some strategies to improve crop survival under water stressed conditions. There are different strategies to overcome the reduction of plant growth due to lack of water and drought e.g. promotion of root growth to absorb water more efficiently form soil through the plant hormone (ethylene), which contributes to inhibiting the growth of roots significantly [10] [11]. In this review article, the relationship among water and crop production in context of effective irrigation, transpiration and photosynthesis, water use efficiency, and growth and yield formation have been discussed.

2. Insufficient Irrigation & Crop Development & Growth and Yield Formation

Insufficient irrigation or limited irrigation or evapotranspiration deficit irrigation is a situation where the actual evapotranspiration of the crop is less than the potential evapotranspiration, which means that irrigation amount cannot fully meet the crop water requirement. For several years, intensive research has been focused on irrigation water to improve water efficiency in agriculture [12] [13]. For example, the impact of water deficit on sorghum before every irrigation was found to be reduced only when the relative effective water content of the soil was decreased to 25%, proposing the effectiveness of water-limited irrigation [14]. Nevertheless universally applicable solutions are difficult to take be developed due to specificity of agricultural practices and types of crops cultivated. However, selection of appropriate crops, appropriate timing for irrigation, effective irrigation techniques and the use of alternative sources of water for irrigation can result maximum water management in agriculture field [15].

2.1. Drought Resistance Index (DRI)

The drought resistance index (DRI) or "reduced yield reduction" is an effective way to express the average yield reduction of water shortage, and it is considered that the crops with moderate water deficit can still obtain higher yields (yield under stress as percent of yield under non-stress conditions) [16] [17]. It is obtained through the comparison of the growth pattern of the main crops under the full and non-sufficient irrigation. It has now become a theory of regulated deficit irrigation. Also, the controlled alternative irrigation was proposed on the basis of comprehensive consideration of the time adjustments, the optimal allocation of water quantity and the function of crop root system to improve water use efficiency [18]. WUE has played a positive role, when applied to crops such as grain, and fruit trees. It has achieved significant water-saving effects and high product quality. In addition, one of the important theories of deficit irrigation is that crops have an effective effect on limited water deficits. Under the adverse conditions of moderate water deficit, crops have certain adaptability and low resistance to limited water shortage [19] [20]. Therefore, moderate water deficits don't necessarily result in a significant reduction in yield, but rather a significant increase in crop water use efficiency [21] [22] [23]. The early shortage of moderate water can conducive to increase yields in cereal crops. The main method is to change the distribution pattern of nutrients in crops, and the distribution of assimilates from vegetative organs to reproductive organs such as the redistribution of nitrogen (N) is capable of promoting root crown development and root canalization [24] [25].

On the other hand, moderate water shortage in the late growth stage, promote the filling process, and accelerate the filling rate, while the material transportation in the crop does not decrease as a result the economic output increases, whereas the severe water deficit reduces the crop yield [26]. The main reason is that the leaf growth slows down or even stops, the leaf senescence accelerates the leaf area and photosynthetic potential decrease, the photosynthetic "source" is seriously damaged, and the lack of assimilation products leads to the early abortion of the grain [27]. One of the most important meanings acquired by the concept of adaptation to drought is the plant's ability to produce acceptable production under drought conditions. Adapted plants are those that are likely to resist a certain water deficit and can produce at an acceptable level compared with another plant that is not adapted to drought [28]. Plants respond to water stress with different mechanisms that vary from specie to specie, which can't be separated from each other because they may be integrated [29]. Dib & Monneveux [30], noted that the complexity of physiological phenomena to cope with water deficit in solid wheat. The concentration of proline in plants exposed to water stress was recorded, which leads to the drying of old leaves and reduced ability to absorb water from the edge of the plant, which ultimately leads to reduced production.

2.2. Previous Studies

Several studies on the source-sink relationship after drought and rehydration at the flowering stage of maize showed that drought reduced the number of grains per panicle corresponding to unit photosynthetic potential under light, medium and heavy water deficit, resulting in relatively sufficient source-sink and increased grain weight [31] [32]. However, due to the feedback regulation of the reservoir to the source, the increase of grain weight was relatively small. Furthermore, the effects of water deficits on crop growth and yield are different in different periods [33]. The water deficit in wheat jointing stage had the greatest impact on the leaves, and the heading stage had the greatest impact on stems, while the maturity stage had the greatest impact on the panicles [34]. The highest direct effect of green leaf area per plant was on dry weight of panicle, and the direct effect of dry weight of leaf stem and sheath was on dry weight of panicle [35].

In addition, many researchers have been conducted to study the effect of progressive drought and mild drought on maize. Acevedo *et al.* [36] discovered that mild drought in the vegetative growth period of maize did not cause a reduction in final leaf area, but only delayed growth. Since the restoration of water supply after water deficit has a compensating effect, water supply after short-term moderate drought can compensate for part of the losses caused by drought. But long term moderate stress or severe stress will cause metabolic disorder and growth decline. The water critical period of maize yield was before and after silking, that defined heading and yield loss of more than 50% during drought stress. The flowering period (Anthesis) and embryo sac abortion resulted in a sharp decrease in panicle grain number, which was the main effect of the drought. The water deficit at the beginning of silking stage and grouting decreased the number of grains in panicle, and decreased grain weight in panicle after pollination, but had little effect on grain number in panicle [37]. In terms of the degree of deficiency, only grain weight was affected under mild and moderate drought, while both grain weight and grain number were affected under severe drought [38]. Moreover, the critical period of crop water deficit is not the same as the optimal water supply period, but there is a time mismatch. Therefore, moderate water deficit at some growth stages of crops plays a positive role in promoting high yield of crop groups, but there are also great risks. Whereas, Mi *et al.* [39] found that grain yield was significantly reduced by progressive drought during vegetative or reproductive period.

On the other side, leaf water potential is an ideal indicator of soil water deficit, and it is supported to indicate soil water deficit by leaf water potential. For this situation, leaf water potential was used to guide the irrigation of cotton fields, which enhanced the WUE compared with soil water potential [40] [41]. Therefore, through multivariate analysis, the functional relationship between leaf water potential, evaporation potential, soil available water, air temperature, and other factors are recognized to indicate soil water deficit and make irrigation decisions, which can reduce the risk of deficit irrigation and obtain obvious benefits [42] [43].

3. Insufficient Irrigation and Absorption of Crop Water, Transpiration and Photosynthesis

The concept of soil, plant and atmospheric continuity (SPAC) is the method to convey water from the soil through plants to the atmosphere, which was proposed by Philip [44]. The concept is recognized that the sphere with all its components (plant, soil, animal and ambient atmosphere combined) forms an integrated physical, dynamic system that is the flow of various processes that incorporate energy and materials occur simultaneously and independently such as bindings in the chain [45] [46] [47]. There have been many studies in China which focused on the (SPAC) water flow dynamic simulation model to simulate the dynamics of soil and crop water conditions [48] [49], which enabled the study of soil, crop and atmospheric water relationship to be entered into a new stage. Therefore, the relationship between root water absorption and soil moisture is the basis of soil-plant-atmosphere continuum (SPAC) dynamic simulation research. Shape of vertical apportionment of plant roots controls nutrient uptake and plant water and affects different processes of soil under field conditions. Nevertheless, information about the distribution of root in the whole rooting shape is infrequently obtainable in practice [50] [51]. In addition, Elias Fereres *et al.*, [52] reviewed the irrigation of the perennial and annual crops, and deficit irrigation use in decreasing consumption of water for biomass production. They concluded that the level of irrigation supply under the irrigation deficit should be relatively high in most cases, which allows realizing 60% to 100% of whole evapotranspiration. Furthermore, they reviewed many cases on the positive use of controlled deficit irrigation in vines and fruit trees, presenting that controlled deficit irrigation not only rises water productivity, but also farmers' incomes.

On the other hand, there is a complex non-linear relationship between root growth and water absorption, where the relationship between the rate of absorption of root water and the density of the root length of the soil unit has a direct correlation, whenever the root system has increased, the capacity of water absorption and water absorption also increased [53] [54] [55]. Additionally, when the soil water is deficient, water absorption of the crop has little relation with root density, but is significantly influenced by the length of the root system. Where the deep root system more suitable to resist dryness of soil from the shallow root system [56] [57]. Furthermore, the crop roots size, number and distribution can be adapted according to soil moisture and nitrogen nutrition. Therefore, in the case of irrigation in the early stage, whenever a larger root system, the root supply more is efficient than the limited supply of water, but the root depth can be shallower than the limited irrigation [58] [59] [60]. The increase of soil water deficit and reduction in the application rate of nitrogen fertilizer is beneficial for root dry weight, but has a little effect on root length. Under severe water deficit, nitrogen nutrition has a synergistic effect on root growth, especially on roots quantity [61] [62]. Therefore, the adaptability of crop roots to soil moisture and nitrogen nutrition is considered as the basis of crop drought resistance and high yield under water deficit conditions.

A reduction of crop photosynthesis caused by deficit irrigation is a major cause of crop yield reduction under drought conditions, and the main reasons for the decline in photosynthesis caused by different deficit strength and time [63] [64]. Under moderate water deficit conditions, the main cause of decline in photosynthesis is stomatal limitation. When the stomata are closed, the stomatal conductance is lowered, and the diffusion resistance is increased, which results in a decreased photosynthesis [65] [66]. In addition, under severe water stress conditions, the decline in photosynthesis is mainly caused by non-porosity limitation, where the damage of chloroplast structure and function and the resulting series of physiological and biochemical changes have caused a decline in crop photosynthesis under moderate water deficit conditions [67] [68]. Crop transpiration rate is limited by many factors [69] [70]. When water is the limiting factor, the change is more complicated [71]. Generally, as the water supply decreases, the transpiration rate decreases. However, according to the optimal regulation theory of stomatal function, when the transpiration of crops is certain, the adjustment of stomata will keep the photosynthesis of crop leaves at a certain level, and the ratio of photosynthesis to transpiration will be the highest, without sacrificing photosynthesis [72] [73]. The purpose of reducing transpiration rate under the premise is to provide a new theoretical basis for crop limited irrigation.

4. Insufficient Irrigation and Crop Evapotranspiration, Yield and Water Use Efficiency

The water and fertile soil are the available renewable resources [74], and the water has become of the most valuable resources on the earth, in terms of the growing interest of the international agricultural community day after day to find irrigation methods that would maintain water and fertile soil [75]. The excessive use of water resources of our planet has been increasing, which requires making critical decisions concerning the use and distribution of water, in addition to implement programs that allow water conservation, especially by farmers, industrialists and all consumers [76]. There are several studies conducted on the effect of insufficient irrigation on yield and water use efficiency. For example, Donk *et al.*, [77] studied the effect on content of soil water and corn, soybean yield. their results displayed that the plowing low or (reduced tillage), with the presence of more crop residue on the soil surface, saves water, increases the yield and decreases pumping cost under insufficient irrigation, whereas more water can be obtainable for challenging needs. Similarly, Guoqiang Zhang *et al.*, [78] reported that the irrigation interval can help conserve a suitable soil-moisture environment in the upper-60-cm soil layer, decrease evapotranspiration and soil-water evaporation, and produce the great yield and water use efficiency. In addition, Agele Samuel *et al.*, [79] investigated the variability in the water use efficiency, water use pattern (ET) and fruit production of field grown rain-fed and irrigated tomato through the late planting season of Nigeria. Results showed that the rain-fed tomato improved crop biomass (root & shoot dry weights) and leaf area by irrigation, and enhanced growth was escorted by high fruit productivity and water use efficiency.

4.1. Evaporation

It is the process by which water turns from liquid to gaseous form, from sea and ocean surfaces as well as from exposed water surfaces such as reservoirs, waterways and lakes [80]. Evaporation calculations are of great importance when designing reservoirs and calculating water requirements for irrigation projects. Whereas, evaporation as a part of precipitation is very difficult to calculate but it still has a great hydrological significance. During the water falls from the air, there is a part of it falls onto the plants (interception) and remains stuck until it evaporates and returns to the atmosphere. Moreover, the evaporation from an aqueous surface means the net amount of water rising to the air from that surface [81]. Therefore, several researches have been conducted in this section, for example; Lascano *et al.*, [82] studied the effect of evaporation on into soil and plant between wheat and cotton crops using the numerical model ENWATBAL. Their results showed that Et for each season was comparable in both systems and the cumulative evaporation of soil water was 50% of Et in traditional cotton and 31% of Et in wheat-stubble cotton. On the other hand, Chen *et al.*, [83] investigated the impacts of straw mass and straw mulching on soil evaporation, temperature, water use efficiency (WUE), crop growth and yield of winter wheat (Triticum aestivum L.). Their results exposed that the presence of straw on the soil surface reduced the extreme, but improved the minimum daytime of soil temperature. Mulch reduced the evaporation of soil by 21% under less mulching and 40% under more mulching compared with control sample, depending on daily measuring of microlysimeters. Nevertheless, because the yield was not improved, the total of water use efficiency was not enriched by mulch.

4.2. Factors Affecting Evaporation

There are many factors affecting evaporation such as; solar radiation (SR), air temperature (AT), vapor pressure (VP), wind speed (WS), and atmospheric pressure (AP) [84]. In addition, the evaporation from soil is affected by the degree of soil moisture, for example, the evaporation of saturated soil is the same of the evaporation from an aqueous surface, where the dry soil has no evaporation. As well as, the quality of water also affects the rate of evaporation, e.g. the rate of evaporation from the sea is less about 2% than in the case of fresh water at the same conditions. The researcher Granger [85] was conducted his work on a field study of open water evaporation on three small lakes in Northern and Western Canada. Model was examined using two independent data sets, his results reported that the modeled evaporation follows the noticed values very good, and responds to changes in environmental conditions. On the other hand, Balugani *et al.* [86] reported that in arid and semi-arid areas with scattered vegetation, the evaporation of neglected groundwater is often considered a relevant contribution to the evaporation process, and water vapor flow should be taken into account when calculating the depth of extinction.

The evapotranspiration is an essential process in agricultural production, where it is associated to biological processes that take place in the plant. The ratio between them is called transpiration rate which is 200% - 500% for wet regions and twice as high in dry regions [87]. Therefore, in the period from the mid-to-late 1980s the improvement of water use efficiency and establishment of a reasonable relationship between evapotranspiration and yield was the focus of theory and practice of using limited water to increase crop yield in water-scarce areas [88]. Many researchers have explored the main limitations to the further raise of crop productivity (with increasing resource use efficiency) and the environmental quality protection (**Table 1**) [89] [90] [91].

When there is insufficient water, there is a significant linear relationship between crop evapotranspiration and yield, and the yield increases with the increase of evapotranspiration. After the evapotranspiration exceeds a certain value, the relationship with the yield is linearly shifted to the parabola, and increasing the amount of irrigation results in a decrease in water use efficiency [92] [93] [94] [95]. Furthermore, due to the difference in water sensitivity of crops at different growth stages, limited irrigation is carried out at different stages of the crop. Even if the evapotranspiration is similar, there will be significant differences in crop yield and water use efficiency (**Table 2**) [96] [97].

This difference of the above mentioned methods is on the basis of moisture of different crops and soils. Therefore, the establishing a reasonable relationship between evapotranspiration and yield in water-scarce areas is one of the theoretical bases for guiding limited irrigation [99]. On the other hand, the water response model (WRM) is a mathematical simulation of the effect of time and quantity of water supply on crop yields (**Figure 1**) [100].

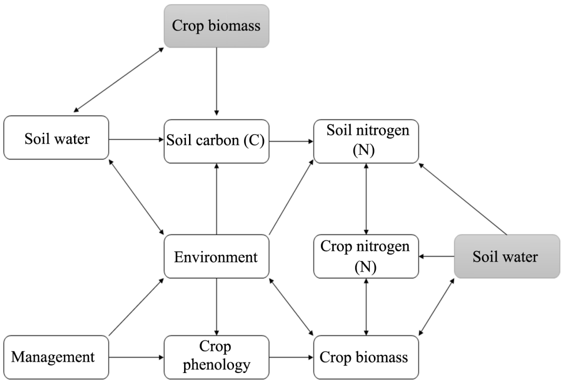

Figure 1. The ranking and interaction (one- and two-way) for each sub-model. Shaded sub-model are iterations presented here to simplify the scheme by reducing the number of crossing lines. Source: [101].

Table 1. Farm-level assessment of the performance of integrated crop nutrient management in major cereal farming systems in 110 agricultural provinces of China [89].

Year	Crop type	Site No.	Yield increase ($kg \cdot ha^{-1}$)	Yield increase (%)	PFP-N increase (%)
2008	Rice	171	590	9.2	11.0
	Maize	139	629	10.7	10.5
	Wheat	67	521	12.6	18.5
2009	Rice	267	785	10.2	14.1
	Maize	257	1092	14.6	16.6
	Wheat	115	518	9.9	12.8

Table 2. Comparison of available methods for determining crop water use and level of adoption by Florida's vegetable industry. Source: [98].

Method	Principle	Advantages	Limitation	Level of Adoption by Industry
Historical potential evapotranspiration	Weather data from the past 30+ years are averaged to estimate ETo	IFAS recommended method crop water use (ETc) simply calculated as ETc = Kc × ETo, where Kc is the crop coefficient	Year to year variability may be ±20% of the historical average most Kc values available are for bare-ground production	None
Real time potential evapotranspiration	ETo is computed daily using site-specific, current weather data	Data more available as the FAWN system expands Increasingly attractive as the cost of small, on-farm weather stations keeps decreasing Crop water use (ETc) simply calculated as ETc = Kc × ETo, where Kc is the crop coefficient. Variable Kc allows daily irrigation adjustment depending on crop age and weather demand. Likely to be part of BMPs	Most Kc values available are for bare-ground production	Currently limited, but with real potential
Class A pan evaporation (Ep)	ETo is related to water loss from a free water surface	Crop water use (ETc) simply calculated as ETc = CF × Ep, where CF is the crop factor. For practical purposes, CF and Kc can be interconverted Principle can be used with pans other the expensive class A pan Variable Kc allows daily irrigation adjustment depending on crop age and weather demand Possible alternative BMP method	Most CF values available are for bare-ground production Old method that was not adopted widely	Virtually unused; should be replaced by the method above
Atmometers	Water loss from a ceramic plate with a canvas cover mimics ETo	Simple principle: water loss from a small surface closely estimates ETo Units are rather inexpensive	Calibration data usually not available	None
Empirical methods	Rely on experience and individual knowledge to estimate irrigation needs	Simple to implement Most farmers' favorite	Based on experience, rather than science Typically results in over irrigation early in the season, and sometimes under-irrigation during peak demand periods Likely to be insufficient in the BMP era	Industry standard

The dated water production function (DWPF) is another useful tool in estimating alternate strategies of irrigation, where it reflects the quantitative relationship between crop yield and evapotranspiration [102] [103]. The investigator De Wit [104] established that the linear model based on the relationship between crop factors and management measures on yield, reflects the same yield reduction effect of water shortage at different growth stages and the average sensitivity of water deficit during the whole growth period [105]. In addition, the multi-model of multi-stage water shortage uses the mathematical formula of multiplication function to consider the mutual effect of multi-stage water shortage [106]. However, the additive model only considers the single effect of water shortage in each stage, and implies that the total effect of water shortage on yield is summed by the single effect of water shortage in each stage. The level of the crop's moisture sensitivity coefficient represents the degree of impact of water shortage on crop yield at different stages and changes due to environmental fluctuations. The establishment of the crop stage water production function and the confirmation of the water shortage sensitivity coefficient are the theoretical basis for guiding limited irrigation [107].

5. Conclusion

In conclusion, the research on crop-water relationship has made significant progress. However, domestic research started late, especially on the characteristics of crop evapotranspiration yield effects, and its influencing mechanisms and regulation principles under limited water supply conditions. Furthermore, the results of limited irrigation research still have great risks and little artificial regulation when applied to production. Therefore, the research in this aspect will become the focus of irrigation attention in the future to provide water, where it is the most important theory to study water saving farming techniques, limited irrigation techniques, modifying the structure of agriculture and water resource distribution technology, and establishing irrigation system to save water and optimal production type of crops. Also, it is the most important theory for the research on water regulation mechanism, a comprehensive model for the production of water, fertilizer and optimal allocation of agricultural technology measures. For the future recommendation, there are many methods that can contribute to provision of irrigation water use, especially in regions that suffer from limited irrigation water. therefore, one of the methods to be considered in the future is to investigate the sustainability of the drip irrigation system through long-term experiments, which can help to save water and provide crop production.

Acknowledgements

This study was supported by national key research and development Projects (No. 2017YFD0201508). Furthermore, the authors acknowledge the valuable help of Gansu academy of agricultural sciences (GAAS), Lanzhou, Gansu, China,

730070.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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