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Review Article

Agronomic Practices to Improve Water Use Efficiency

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Abstract

Water scarcity, which already occurs for more than a billion people worldwide, will worsen further, and the water supply available for future generations, especially for use in agriculture, will be increasingly restricted (FAO, 2017). Above all, in arid and semi-arid regions, irrigated agriculture uses more than 70 to 80% of the total water available and is essential to increase food production in these regions, where the population is rapidly increasing (TURNER, 2004) [1]. The world's population in 2004 was more than 6,000,000, of which around 5,000,000 were in developing countries, and 20% of this population has remained undernourished since the 1990s [2]. For this time, water management in agriculture, in the current era of scarcity, should be engaged to implement water use efficiency (WUE), spending fewer resources and producing less expensive plant protein [3,4]. In the past, during the post-war "green revolution", the paradigm of agriculture was to modify the environment (heavy fertilization, irrigation, and mechanization, with energy expenditure) to adapt it to the plant, with the generation of so-called high-yield varieties (HYVs), with high harvest index (HI: Dry Weight [DW] of the organ harvested. plant DW-1), for mechanized harvesting and responsive to the application of fertilizers, which were cheap at the time [1], but less adapted to the stresses, which was mitigated by energy expenditure, in irrigation and mechanization, and fertilizers applied [5]. For example, in grasses, the induction of progressive tillering, as occurs in the millet and sorghum, is one of the mechanisms of escape from environmental stresses because each inflorescence will have a different period of fertilization increasing the chances of producing some viable panicles [5]. However, this characteristic would prevent mechanized harvesting, but small farmers in marginal areas of agriculture do not use mechanic harvesting. Marginal agriculture areas are frequently subjected to environmental stresses and have soils with poor nutrient content [3]. In the past, during the green revolution, it was always a characteristic undesirable for plant breeding programs to improve yield. In addition, the increase in HI was often obtained with a reduction of volume and root area, which is very important to implement the WUE [6]. Therefore, the genetic basis for the environmental adaptation of the most improved crop by man, such as maize, has been dramatically diminished. After the oil and energy crisis in the 1970s, the paradigm of agriculture has become to modify the plant to adapt it to the environment, with WUE, generating varieties with Low Technological Cost (LCVs) for agricultural production (Figure 1). This adaptation to environmental stresses can also be found in local landraces used by the small farmers living in marginal areas for agriculture, which needs to be better studied and recommended to increase food safety in these areas [3].

Introduction

Water scarcity, which already occurs for more than a billion people worldwide, will worsen further, and the water supply available for future generations, especially for use in agriculture, will be increasingly restricted. Above all, in arid and semi-arid regions, irrigated agriculture uses more than 70 to 80% of the total water available and is essential to increase food production in these regions, where the population is rapidly increasing [1]. The world's population in 2004 was more than 6,000,000, of which around 5,000,000 were in developing countries, and 20% of this population has remained undernourished since the 1990s [2]. For this time, water management in agriculture, in the current era of scarcity, should be engaged to implement water use efficiency (WUE), spending fewer resources and producing less expensive plant protein [3,4]. In the past, during the post-war "green revolution", the paradigm of agriculture was to modify the environment (heavy fertilization, irrigation, and mechanization, with energy expenditure) to adapt it to the plant, with the generation of so-called high-yield varieties (HYVs), with high harvest index (HI: Dry Weight [DW] of the organ harvested. plant DW^{-1}), for mechanized harvesting and responsive to the application of fertilizers, which were cheap at the time [1], but less adapted to the stresses, which was mitigated by energy expenditure, in irrigation and mechanization, and fertilizers applied [5]. For example, in grasses, the induction of progressive tillering, as occurs in the millet and sorghum, is one of the mechanisms of escape from environmental stresses because each inflorescence will have a different period of fertilization increasing the chances of producing some viable panicles [5]. However, this characteristic would prevent mechanized harvesting, but small farmers in marginal areas of agriculture do not use mechanic harvesting. Marginal agriculture areas are frequently subjected to environmental stresses and have soils with poor nutrient content [3]. In the past, during the green revolution, it was always a characteristic undesirable for plant breeding programs to improve yield. In addition, the increase in HI was often obtained with a reduction of volume and root area, which is very important to implement the WUE [6]. Therefore, the genetic basis for the environmental adaptation of the most improved crop by man, such as maize, has been dramatically diminished. After the oil and energy crisis in the 1970s, the paradigm of agriculture has become to modify the plant to adapt it to the environment, with WUE, generating varieties with Low Technological Cost (LCVs) for agricultural production (Figure 1). This adaptation to environmental stresses can also be found in local landraces used by the small farmers living in marginal areas for agriculture, which needs to be better studied and recommended to increase food safety in these areas [3].

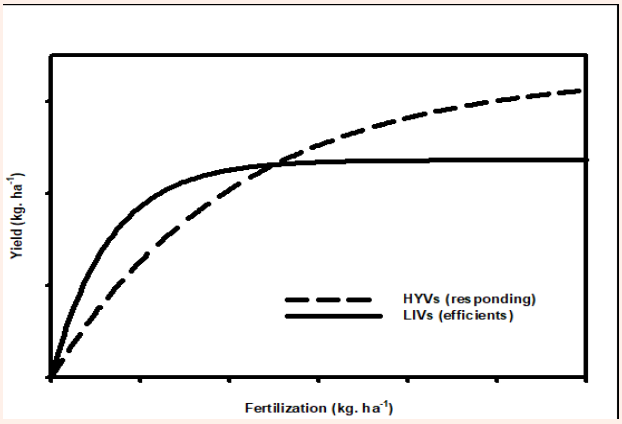

Figure 1: Response of high-yield varieties (HYVs) and Low Technological Cost (LCVs) to fertilization associated with the need for irrigation (NI).

What is WUE?

The WUE can be assessed both from a physiological and agronomic point of view [5]. Physiological WUE is the relationship between the rate of photosynthetic assimilation of CO_2 (A) and the vegetable's transpiration rate. At the same time, the agronomic is the relationship between the dry mass produced by the volume of water used during the cycle (precipitation plus irrigation water) in the cultivated area. The water content in the plant is the result of the balance of water absorption rates by roots and water loss by the transpiration of leaves. The first factor is out of instantaneous control (the root conductivity [Lp] is variable, depending on water absorption pathways, and it takes longer to change), being dependent on the physiological characteristics of the plant and other characteristics of the medium [5]. The second factor, the control of transpiration, can be done in minutes and on a greater or lesser scale, depending on the vegetable, through control of the stomatal opening to interfere more quickly with WUE. In general, the C_3 plants have a WUE ranging from 1 to 3 g of fixed CO_2. kg^{-1} of transpired H_2O. However, for C_4 plants, this WUE ranges from 2 to 5, and for CAM plants, WUE varies from 10 to 40. The high WUE of C_4 plants is because they have a mesophilic conductance higher than C_3 plants due to their higher rate of carboxylation, a greater affinity for substrate, and absence of photorespiration. With this greater mesophilic conductance. C_4 plants may have stomata less open, saving more water. Meanwhile, field comparative studies with wheat (C_3) and corn (C_4) showed that WUE in the culture of these plants is similar as other physiological factors play a role, such as more significant osmotic adjustment and other mechanisms for adaptation to drought, more developed in wheat than in corn. So this higher WUE of C_4 plants allows their cultivation with a lower water consumption per mass produced in the irrigated crop of C_4 plants. However, under water deficit conditions, wheat (C_3) and peanuts (C_3), for example, are more tolerant and productive than maize (C_4) due to other physiological attributes [7]. Therefore, the WUE is vital for agriculture, especially in low water availability conditions, but does not guarantee drought tolerance. However, one of the plants grown mainly in arid regions, which is one of the crops more drought tolerant, the pearl millet (*Pennisetum glaucum*), has as its main characteristic of adaptation to drought the rapid development in depth of its root system, associated with efficient stomatal control [5] . Analyzing a canopy of cultivated plants, in addition to the loss of water by transpiration by plants, the evaporation of water directly from the soil should be evaluated in the simultaneous process called evapotranspiration, which can be calculated or measured. Also, evaluating the evapotranspiration during the plant cycle in cultivation can be made a forecast of yield. Depending on the evapotranspiration culture location, one can calculate the productivity of that crop in that location. According to [8], the dry mass production of a crop, depending on the evapotranspiration, is calculated by the equation:

$$Y = m.\ T.\ E^{-1}$$

Where Y is yield, m is a culture-specific proportionality coefficient, T is the transpiration, and E is the daily average of evaporation, in the class A tank, during the plant growth, which is a function of the site of the crop. The water evaporation component direct from the soil is not controllable, as is the plants' transpiration; therefore, soil with vegetation cover loses less water to the atmosphere, conserving it. Thus agricultural techniques currently recommended should keep the soil covered during the year, as the No-Tillage System (NTS), agroforestry, use of green manure, and other agronomic stoneware bring benefits to the use and saving of water in the agricultural system [5].

Strategies to implement the WUE of cultivated plants

The plant may suffer from a water deficiency caused by the atmosphere, when the water Vapor Pressure Deficit in the atmosphere (VPD) is high, or by the soil when there is a lack of water in this, and both induce stomatal closure. For the atmosphere, the water potential gradient (Ψa) between the plant and the air is, most often, much larger than the gradient between the soil and the plant [5]. Thus, the most significant limitation to the flow of water in the Soil-Plant-Atmosphere Continuum (SPAC) occurs at the level of water absorption by the root system because the gradient between the soil and the root, and the maximum root Lp is smaller than the maximum gradient and conductivity between the plant and the atmosphere. Thus, to control the loss of water, plants close the stomata. However, with the decrease in stomatal conductance(gs), A is reduced, affecting dry mass accumulation. Another characteristic for implementing the WUE for pearl millet grown in the arid region of the Sahel African area is the maintenance of the green leaf area, reducing senescence, for the recovery of the plant after a short-term drought associated with an accumulation of carbohydrates in tillers, with re-translocation for grain filling in the viable tillers, ensuring grain production after drought.

Increased water absorption by plants

Root water absorption is of great importance to WUE, mainly in marginal areas for agriculture, and the depth and spread of roots are the most important characteristics, according to [1]. In addition, the root system also synthesizes and accumulates phytohormones (ABA, Auxins, Cytokinins, and others), which are partly responsible for the modulation of root growth, along with other aerial phytohormones and environmental factors. The development of the root system is highly plastic, depending on the characteristics of the soil where the plant develops and, therefore, the roots developed in the field have characteristics quite different from those grown in pots; the results obtained in a pot should not be extrapolated to the field of cultivation [7,9] showed that a shrubby species, *Ziziphus mauritiana*, performed osmotic adjustment when submitted to drought in pots, while in the field, avoided desiccation with its deep root system reaching the wettest layers of the soil. The root system's efficiency in absorbing water and nutrients depends on many genes [7], to characterize its depth, volume, area, Lp, the profusion of root hair, longevity, and other attributes [5]. A strategy for assessing the potential of development of the root was proposed by [6] when assessing the starch content in seedling roots in a large number of genotypes of cotton and those selected for high starch content in the roots had advantages in development and productivity in the field, under rainfed cultivation.

Reduction in water losses by plants

The control of transpiration is mainly done by stomatal closure reducing gs, which is the SPAC process that has a faster response. However, such control is associated with the supply of CO_2 to the leaf, and if the gs is kept too low for too long will impair CO_2 assimilation [5]. Therefore, in the hottest hours of the day, even in irrigated cultivation, it may be necessary for the plant to reduce its gs and water flow from the plant to the atmosphere so there is no severe dehydration. Nevertheless, it should also be noted that many C_3 plants in arid climate regions have great stomatal control and consequent high WUE [9] . A technique for selecting plants that are more efficient in water use is to evaluate the relationship between A and gs; reducing water losses by transpiration is the intrinsic efficiency in the water use (IWUE: A. gs^{-1}). The IWUE, when evaluated at the pre-flowering stage of common bean, the most sensitive stage because embryo growth depends on maintaining high A, was used to discriminate genotypes with high IWUE (Figure 2).

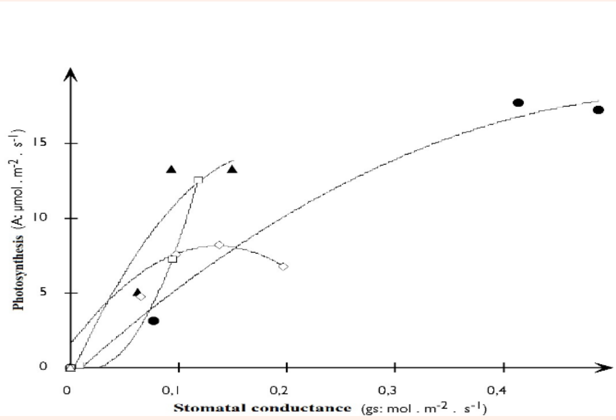

Figure 2: Intrinsic water use efficiency (IWUE), i. e. the relationship of photosynthesis (A) with stomata conductance (gs) of four different genotypes of common bean, when evaluated at the pollination stage.

Recommendation of crops with tolerance to drought

During the last 400,000,000 years of plant evolution, with the pressure of dry and hot environments, outside the seas, plants have emerged more adapted to the different environments where they evolved. Because agriculture is approximately 10,000 years old, the selection process done by men cannot be compared, mainly by the number of generations involved, with natural selection occurring in the most hostile environments during the evolution of plants [10]. Thus, native plants from marginal areas of agriculture, which are subject to a lack of nutrients, such as millet and sorgo, are better adapted to these stresses when compared to species originating in wetter and higher fertility soils, such as maize. Therefore, it is necessary to identify the characteristics of cultivated plants that are more tolerant to drought, which can ensure agricultural production in these marginal environments [5]. Among these plants adapted to high temperatures and drought, some will maximize water absorption or are associated with optimizing the use of water absorbed for dry matter production [9]. Other physiological characteristics allow the plant to avoid the dry period, shortening or prolonging the cycle. Nevertheless, the third type of character is related to the capacity of the plant tissue to tolerate a low content in water, maintaining its activity [5]. Therefore, drought and high-temperature tolerance are considered multigenic characteristics. Many of these genes are identified, in gene patent banks, with more than 2,800 patents for tolerance of stresses. Nevertheless, most of these genes are associated with a metabolic route, with dubious significance at the level o the field, and there is still no organism genetically modified that is proven to be drought tolerant after dozens of years of research [7]. Therefore, it is not enough to seek a single process and its genetic control to transform a sensitive plant into a drought-tolerant plant. For example, there is no use for cultivation in marginal areas if a plant can synthesize stress-protective compounds, if it has a very water-permeable epidermis, quickly losing water to the atmosphere, or if it has a little deep and inefficient root system in capturing water, as common bean [5]. A drought tolerance mechanism very studied is the active accumulation of osmotic solutes in the cell, called osmoregulation, which allows the maintenance of turgescence, growth, and photosynthesis under low leaf Ψa values [11]. The phenomenon of osmotic adjustment is variable between species and between varieties of a species. For example, corn, millet, and sorghum make an osmotic adjustment, but corn does little when compared to the other two species, while between millet and sorghum, the latter makes a more significant osmotic adjustment [5] but is no longer tolerant of drought than pearl millet [5]. However, according to [11], the evaluation of osmotic adjustment in corn, as a characteristic of drought tolerance, was not correlated with corn yield under water deficiency, as it has low heritability and little progress can be expected for the selection of this character. Therefore, it is more interesting that for the increase in food production in marginal areas for agriculture, the use of genotypes of species also native to these marginal areas were selected in a similar environment [3]. Most crops' degree of adaptation depends on the species' origin center [10]. In Northwestern Brazil, for example, the cultivation of crops adapted to drought, such as cowpea, groundnuts, oil palm, or *Atriplex nummularia*. This forage halophyte is very drought tolerant (originated in North Africa and the Near East and was introduced in the Northwestern of Brazil). For cereals, sorghum and pearl millet are water stress tolerance (originated in the Sahel of Africa), and the legumes are cowpea, groundnut, and pigeon pea. Those crops used as human food could help to increase agricultural production in this marginal area for agriculture, as these species are more adapted to drought than maize or common beans [5]. Therefore, the simple agricultural zoning of marginal regions for agriculture, where the population growth is fast [3] and the indication of the species more adapted to local stresses, with technical monitoring of the management of appropriate production, can implement the agricultural production, with more significant water savings [7].

Physiological parameters for monitoring and selecting plants for high WUE

Plant Physiology has been of little help in improving irrigation management due to the lack of rapid methodologies and equipment capable of monitoring and discriminating a large number of genotypes, according to [5]. However, rapid collection methods for subsequent metabolites dosages [6], and modern equipment, cheap with rapid measurements, which are being developed, allow the rapid monitoring and plant selection for WUE [4]. Currently, the use of rapid and remote sensing of leaf temperature, plant or canopy, with cheaper equipment such as the thermometry sensors [1] or infrared aerial images, allows the measurement of the canopy temperature, which is compared to air temperature can indicate, indirectly, the water status of the plant or crop. Another equipment of interest is the sap flow meter, which indirectly assesses the transpiration rate. Both types of equipment can be used for remote monitoring, necessary for the recommendations for irrigation management [4], such as Controlled Deficit Irrigation (CDI) or Partial Root Drying (PRD), described below. In addition, other equipment, such as the spectroradiometer, with reflectance measurements in the visible and near-infrared spectrum, and the mass spectrometer, with isotopic discrimination of $12CO_2$. $13CO_2^{-1}$, the infra-red gas analyzer (IRGA), which measure the gas exchange of CO_2 and H_2O, and fluorimeters, used for quick measurement of chlorophyll a fluorescence, which is proportional to A. These new equipment are strengthening the cooperation of the Plant Physiologist with the irrigation management and Plants Breeder for plant drought tolerance selection.

Agronomic management to implement WUE

to increase the WUE and agricultural yield of plants to be cultivated in rainfed conditions in small properties of marginal areas for agriculture, the cultivation of plants with greater tolerance to environmental stresses can contribute to a sustainable agricultural system with low use of fertilizers and pesticides, and consequently reduced cost for production of food [1]. There are already several known low-cost agronomic practices, which, having technical accompaniment, can increase agricultural production in these regions, such as the no-tillage system (NTS), agroforestry, green manure, intercropping, high density of planting, and others [5]. In addition to these agronomic practices, other recommendations are the use of Plant Growth-Promoting Microbes (PGPM), such as inoculation of leguminous seeds with *Rhizobium* strains, or in other species, inoculation with other bacteria and beneficial endophytic fungi or rhizosphere fungi [12]. Also, the foliar fertilization with phosphorus, which allows for faster recovery after stress, the use of fungicides of the triazole group, which stimulates the production of nitric oxide to increase photoassimilates export to root. These last two recommendations increase the activity of antioxidant systems and, consequently, the WUE and adaptation to abiotic stresses, such as drought [5].

Agronomic techniques for increasing WUE

Some agronomic recommendations to implement the WUE in marginal areas for agriculture already exist, as has been said, which are lacking in family farming in these regions to increase their production, lowering its cost. A cultivation system that implements the WUE is the NTS, for which the pearl millet crop is important for producing much straw without fertilizer application or irrigation. Soil cover with straw maintains soil moisture, saving water for the main crop, and having other advantages will enable lower crop evapotranspiration than in other cultivation systems [5]. Despite popular belief that larger spacing between plants decreases the risk of reduction in yield in years of drought, another recommendation is the increase in the population of plants. For example, for the cultivation of pearl millet in the African Sahel, the increase in plant population from 5,000 to 20,000 plants. ha^{-1}, which increases yield and the WUE, even in low-fertility soil. In addition, cultivating drought-tolerant crops, such as sorghum or pearl millet, intercropped with tolerant pulses, such as cowpea or groundnut, is recommended. Both kinds of cereal have deep roots, which recycle nutrients, and the pulses do the

BNF, increasing the N content in the soil. Another recommendation to increase WUE is agroforestry, or cultivation in aleas, with tree legumes such as *Acacia* ssp., *Prosopis* ssp., *Faidherbia albida* or *Leucaena leucocephala*, with annual crops intercropped, which reduces the action of winds on evapotranspiration of the crops, and the tree legumes serve as green manure as well (Pimentel, 2006). In addition, the use of green manure, with the incorporation of the green mass produced by *Mucuna spp*., *Crotalaria spp*., *Canavalia spp*., *Vigna spp*., *Cajanus cajans*, among others, can increase N availability and moisture retention in the soil, favoring the next crop, in a crop rotation system [1].

Irrigation management

Globally, more than 40% of irrigation-dependent food production, which is used in only 17% of the agricultural area of the Earth, and seen the increase in the population marginal regions for agriculture, irrigated agriculture is increasing [2]. One of the most used techniques for assessing irrigation need is based on the measurement of potential evapotranspiration (ETo) in a class A tank and calculating the actual Evapotranspiration of The Crop (ETc) and the need for irrigation (NI) for a crop by multiplying the ETo by a crop coefficient (kc), which is found in tables proposed by FAO [1]. However, new techniques of irrigation have been proposed and used to reduce evapotranspiration of the crop such as Controlled Deficit Irrigation (CDI), with a controlled reduction of NI, or Partial Root Drying (PRD), which are used primarily for fruit trees crops, such as for the vineyard in California. However, these techniques require monitoring plant hydration, not soil hydration, as usual for irrigation, for precise control of plant water status and irrigation [4]. For CDI, the NI can be reduced by up to 40% of ETc without causing a significant reduction in yield in citrus, vine, olive tree, and other crops. However, monitoring the leaf Ψa or leaf temperature or sap flow is essential to control the water status of the crop, increasing WUE for small farming systems in marginal areas for agriculture [4]. Another technique already widely used in commercial grape production is the PRD method, according to [1]. This method consists of providing water on one side of the root system, while on the other side, there is a drying of the roots, which sends ABA to the aerial part reducing gs and transpiration without reducing the productivity of the crop. This technique can increase WUE by up to 50%, but it is recommended that the sides, dry and irrigated, of the plant are alternated by cycles of 10 to 14 days so that the concentration of ABA in the leaves is not too high, which can reduce A and yield [4].

Use and inoculation of plant growth-promoting microbes (PGPM) in the agriculture

A cheap recommendation, significant for agriculture in marginal areas for agriculture, soils, is the inoculation of leguminous seeds with strains of *Rhizobium spp*., which increase N supply for the plant through the BNF, causing increased yield and WUE [5]. In addition to this symbiosis, various plants can be invaded by fungi, which form a symbiotic association called mycorrhizas, which promotes an extension of the root area and volume and may increase the absorption of phosphorus and water by mycorrhizal plants. Other endophilic fungi producing ABA, such as the genus *Colletotrichum*, for example, can express a parasitic or mutualistic lifestyle, depending on the host, and as mutualists, can promote more remarkable adaptation to abiotic stresses and increased growth. Some microorganisms that increase agriculture productivity are A*zospirillum, Bacillus, Burkholderia, Enterobacter, Flavobacterium, Pseudomonas, Frankia, Klebsiella, Clostridium, Trichoderma, Beauveria, Serratia* and *Streptomyces*. These bacterias are endophytic or grow in the rhizosphere and stimulate the synthesis of phytohormones in the host plant, increasing growth and WUE and adaptation to abiotic stresses [13]. They promote plant growth as phytostimulator, influencing the phytohormones metabolism by enhancing auxin, cytokinins, abscisic acid, and gibberellins production and reducing ethylene concentration [12]. For example, the inoculation with *Bacillus subtilis*, which produces cytokinins, increased the ABA content in the plant's shoot, increasing its WUE. Some soil fungi can also produce and provide ABA to the plant host. Another *rhizobacterium*, *Variovax paradoxus*, produces the ACC-deaminase enzyme, which degrades ACC, an ethylene precursor, increasing WUE and yield. These microorganisms are already used in agriculture, and there are products on the market called biofertilizers.

Conclusions and Perspectives

The world population is around 8 billion people, and 90% of the current population increase will occur mainly in marginal areas for agriculture in developing countries. According to [3], 20% of the world's population will continue to be malnourished, and food production in these regions needs to be increased for food security in these areas, mainly using adapted crops and low-cost agricultural techniques discussed here. Some sustainable, low-cost agricultural systems need to be developed for the subsistence of small farmers in these marginal areas, which will require constant technical follow-up. Climate changes prevision due to increased Green House Gases (GHGs) concentration in the atmosphere, which will raise the frequency of environmental stresses, such as drought, high temperature, excess precipitation, and other stresses, which will exacerbate the environmental stresses. Therefore, the sustainable agronomic practices discussed above need to be put into practice to prevent hunger and increase food security in the future.

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