Enhancing Water Use Efficiency: Influential Factors, Agronomic Modifications and Potential Oppurtunities

**ABSTRACT**

Plant water use efficiency, ~~or~~ (WUE), is becoming a crucial concern in semiarid regions where a lot of water is needed for crop production. To ensure the environmental sustainability of food production in these regions, WUE must be improved. ~~Boosting~~ crop WUE is essential for sustaining global food supply, as climate change projections call for rising temperatures and dryness in semiarid regions. Since concurrent measurements of photosynthesis and transpiration is made easier by handheld instruments for monitoring leaf gas exchange rates, WUE is frequently studied at the leaf level.

With the rising demand on water resources for agriculture due to population expansion and climate change, crop water use efficiency, or WUE, has gained considerable interest. As average temperatures rise, rainfed crops have issues from an increasing trend in evaporative demand and, in many areas, higher unpredictability and a lower trend in rainfall. Irrigated farming also has to contend with dwindling water supplies and heightened rivalry from other users. First, maximising the amount of water that the crop transpires rather than wasting it would increase agricultural water use efficiency.

Improved early crop vitality and more profound roots are two attributes that should aid in this. It would also increase crop WUE to get more biomass per unit of water transpired. Numerous characteristics have been suggested to address this result. Limiting crop transpiration through reduced stomatal conductance is considered to be less useful than features that increase carbon uptake, such increased mesophyll conductance or improvements to photosynthetic biochemistry and adaptability. The most beneficial results for enhanced crop WUE will most likely come from mixing characteristics to have a synergistic effect.

The outcomes of crop model simulations corroborate the possible usefulness of trait mixes.

***Key words-*** *WUE, photosynthesis, transpiration, evaporative demand, crop vigour, stomatal conductance, carbon gain, mesophyll conductance, crop simulation*

**INTRODUCTION**

In semiarid and arid regions, irrigation is a significant agricultural technique for producing food, pasture, and fibre. Today's top priorities in many nations, including Australia, involve successful water management and utilisation. The majority of irrigation water comes from dams and rivers, and it is transported to irrigated fields via pipelines or open channels where it is stored until needed or applied immediately to the root zones. ~~Storage tanks are a common feature on the sites of aquifer irrigation operators. Sprinkler, surface, drip, and trickle irrigation systems are the three main categories of regularly used irrigation systems or techniques at the farm level. Water is sprayed on surfaces with sprinkler installations (such as solid sets, centre pivots, and moving irrigators) by means of overhead sprinklers. Water is supplied in tiny volumes via tiny nozzles put in pipes or tapes, which can be buried or above ground, in drip or trickle systems. Because sprinkler and drip/trickle systems run at low pressure and frequently require pumping, they are sometimes known as pressurised systems. Gravity pulls water over the field surface in surface systems (furrow, basin, boundary, etc.). The most used technique for watering row crops worldwide, including in Australia, is the furrow system.~~

About 70% of fresh water extracted globally is thought to be utilised for irrigation on 25% of croplands (399 million hectares), which provide 45% of the world's food. [[**1**](https://www.mdpi.com/2073-4441/10/12/1771#B1-water-10-01771)]. Roughly 20% and 10% of the world's total water use is used for commercial and residential purposes, respectively. For example, in Australia, 2.2 million hectares were irrigated with 9.1 million megalitres of water in 2016–2017 [[**2**](https://www.mdpi.com/2073-4441/10/12/1771#B2-water-10-01771)]. Fresh water resources are becoming more and more in demand, and this trend is probably going to continue given the growing population, which raises the need for food and fibre, as well as the anticipated adverse effects of climate change. The necessity of providing enough water to support other ecological functions is also becoming more widely recognised. There appears to be consensus that irrigated agriculture in general is up against a future with less water. This, therefore, calls for increased effectiveness in the utilisation of the scarce water resources, a concept that is technically called water use efficiency (WUE) or simply irrigation efficiency. From an engineering standpoint, WUE is often defined using a volumetric or hydrological approach, simply as the proportion of the water supplied through irrigation that is productively or beneficially used by the plant (Equations (1) and (2)). This definition is predominantly used when referring to field-scale irrigation water management. However, it should be noted that WUE may also be assessed at the catchment or basin scale [[**3**](https://www.mdpi.com/2073-4441/10/12/1771#B3-water-10-01771)].

Biomass of grain yield

Water Use Efficiency

Transpiration or Evapotranspiration

**Figure 1** Generalized view of water use efficiency as a function of the water use by a crop relative to biomass or grain production

#### **Defining Water Use Efficiency**

#### Drought resistance and tolerance have given rise to the principles of water production, or water use efficiency (WUE) (Passiour, 2006). At the beginning of sixties of last Century, water use efficiency has been generally defined in agronomy as:

WUE= Crop yield (usually the economic yield) **………………………………………………… (1)**

Water used to produce the yield

Since crops require a large amount of water (about 70% of the water accessible to humans), and because there are more areas under irrigation in semi-arid countries, water use efficiency (WUE) is a topic of great importance in agriculture. The use of water resources for industry, agriculture, direct human consumption, and other reasons is becoming more and more controversial due to the paucity of available water. Enhancing agricultural water use efficiency (WUE) might mitigate this debate and make WUE a primary objective for food security and agriculture [5-9].

WUE is defined differently based on the practitioner (farmer, agronomic, physiologist, etc.), the scale, and the availability of data. Only a brief overview of these criteria is given here because they are extensively discussed and freely available elsewhere (10,11, 12).

#### The main location for gas exchange between a plant and the atmosphere is the leaf. The ratio of ~~A~~ an to the rate of transpiration (T) is measured instantaneously to determine the leaf water usage efficiency (WUEl). It is also often referred to as leaf transpiration efficiency and is defined as:

#### WUEl = An/T = 0.6ca(1 − ci/ca )/(wi − wa **)............................................(2)**

#### where the ratio of CO2 diffusion to H2O diffusion is approximately 0.6,

#### ci is the [CO2] of the intercellular leaf space, ca is the [CO2] of the atmosphere,

#### wi is the water vapor concentration of the intercellular leaf space, and

#### wa is the water vapor concentration of the atmosphere. This function

#### reveals that, for a given VPD between the leaf and atmosphere (wi − wa),

#### WUEl is regulated by ci/ca, which represents the equilibrium that is reached between the conductance for CO2 entry into the leaf through stomatal pores and the reduction of [CO2] by photosynthetic assimilation in the intercellular air spaces (29).

#### Due of WUEl's high sensitivity to change in time and place, it can be difficult to assess the physiological causes of variance among, say, crop genotypes. As a result, it is typical to compute iWUE at the leaf level as the ratio of ~~A~~an to gs, or to normalise WUEl to a standard VPD (13).

#### This function may be stated for C3 species in a form that highlights the significance of gm and the drawdown of [CO2] in the chloroplast (cc) by An and gs to WUEl (14):

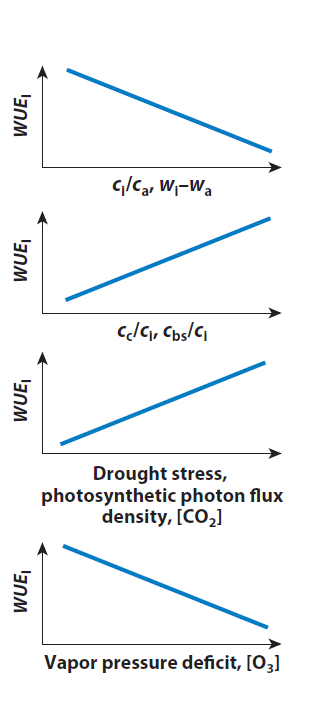
#### iWUE = An/gs = (gm/gs )/(1 + gm/gs ) × (ca − cc ). 2.

#### No equivalent function has yet been derived for C4 photosynthesis, but gm, which for C4 plants

#### reflects the resistance for CO2 to reach phosphoenolpyruvate carboxylase in mesophyll cells from

#### the intercellular airspace, as well as t the extent of bundle sheath leakiness, could potentially limit

#### iWUE in C4 species (15).

**Figure 2** Simplified relationships of *WUE*l with physiological drivers and environmental factors

#### **Factors Affecting WUE**

Enhancement of water distribution networks, development of on-farm irrigation, scheduling irrigation, real-time control and optimised performance, remote sensing, and sensor and communications networks are examples of engineering and technology considerations. These elements primarily increase irrigation WUE by lowering water loss. A wide range of hardware and software devices have recently entered the market and are utilised to improve irrigation WUE. Plant genetics has advanced to the point that disease-resistant, high-yielding cultivars with greater WUE have been created. Growing environmental consciousness has led to the funding of water-saving projects by several governments worldwide, under the condition that the water conserved is returned to the environment as flows. WUE is significantly influenced by socioeconomic variables as well. This section will address this, emphasising the deployment of technology and irrigation water consumers' decision-making procedures.

Farmers must make difficult choices about how to run their businesses when there is a shortage of irrigation water. This is a recurrent issue in Australia, where land is almost limitless but water is a major productivity constraint. Farmers frequently irrigate a portion of their property and use rainwater to grow the remaining area. According to ~~a~~ research conducted in Southern Spain, most farmers who grew intensively irrigated olive trees employed deficit irrigation to optimise the value of the scarce water resources [16].

However, it should be acknowledged that WUE cannot be continuously enhanced. When changes are made to an irrigation system, it would be simpler to see an increase in WUE if the system had initially had poorer irrigation performance. On the other hand, the WUE will rise (if it does at all) at a significantly slower pace for a system that is already running close to ~~at~~ a maximum efficiency.

**Modifications of agronomy for improving WUE**

Drought resistance for a crop can be affected by many agronomic measures. Some measures are critical for improving WUE, and can be achieved with relatively simple changes to production practices.

1. **Planting date**- Early maturing genotypes are better adapted to situations where the time of favourable water supply is short and the danger of water stress is quite high, as short crop duration helps significantly to drought escape (Debaeke 2004). By coordinating the development of crops cycle with patterns of rainfall and temperature to reduce the likelihood of being exposed to water deficit during drought-prone periods, planting dates in conjunction with genotype selection that is appropriate can assist drought escape. Naturally, choosing a cultivar and planting date requires taking into account the thermal environment's suitability for crop establishment and life cycle completion. When the length of the rainy season determines the length of the growing season, planting appropriate cultivars as early as possible lowers the likelihood of experiencing drought during the late grain-filling stage (Heisey and Edmeades 1999)[17]. A modeling approach to selection of planting date– cultivar combinations is included in Birch et al. (2006)[18].
2. **Planting geometry**- WUE can be influenced by planting shapes and patterns, which vary depending on the climate and cultural context. The most popular design is equal row spacing, with rows spaced between 70 and 90 cm apart. Various intra-row plant spacings result in varying densities of plant populations. In order to improve crop dependability, skip row sowing—planting one row not between every two or three rows—has been suggested. This technique limits water usage early in the growing season and keeps a store of water in the soil in the wide row space created by the missing row. However, even though grain sorghum has demonstrated notable yield gains, research by Robertson et al. (2003) [19]and Madhiyazhagan (2005)[20] in Australia failed to show similar benefits for maize, both finding maize does not exploit the water remaining in the wide row space.
3. **Tillage** Conventional tillage and conservation tillage are the two main categories of tillage that are utilised, depending on the amount of organic residues remaining on the soil surface. The findings of several studies conducted in nearly every climatic zone on Earth indicate that ploughing contributes to typical soil-related issues such as compaction, soil erosion, decreased water percolation leading to increased runoff, and high energy and time requirements [21]. While reducing soil erosion is often the goal of conservation tillage, which also includes no-tillage, ridge tillage, mulch tillage, and any systems with at least 30% residue cover left after planting (22), (23), it also improves water infiltration (24), water storage and thus yield potential and improved WUE (25).
4. **Residue retention and plastic mulch**- Up to 50% of a crop's total evapotranspiration might evaporate from the soil's surface in semi-arid regions (26). In addition to having the apparent benefit of lowering evaporation, mulching with agricultural residues may further enhance WUE by lowering surface temperature, improving infiltration, and minimising runoff (25). By shielding the moist layer of air at the surface from the wind and regulating soil temperature, surface mulching often lowers evaporation. Because mulching materials often reflect more solar radiation and have poorer heat conductivity than soil, the maximum soil temperature is frequently lowered (27). Retention of crop residue and minimum tillage improves several measures of soil quality, sustains or improve crop production, and increases WUE of maize in semi-arid subtropical areas (28, 29) and humid tropical areas (30). Plastic mulching is becoming a more popular option for field crops since it has shown to be an effective way to boost the profitability of various horticulture crops. Using plastic mulching on rainfed maize has resulted in significant production gains, more than doubling yields (31). Plastic mulch can raise the temperature in chilly regions that are not ideal for crop development while preventing water from evaporating. The WUE of cotton has risen from 0.49 to 0.76-0.86 kg/m3 (32), thanks to the combination of micro-topography and plastic mulch; nevertheless, the implementation of this technology is contingent upon its cost-effectiveness and the resolution of issues with in-field degradation and the removal and disposal of old plastic film.
5. **Weed control and fertilizer use** While both take advantage of the few resources available at a place, weeds contend with crops grown for food for light, nutrients, and water. Weeds have varying effects on agricultural plants based on their kind and degree of interference. In maize, as in other crops, weed treatment effectively reduces water usage (33). Thus, one tactic to increase WUE is nutrition supply control. For example, Ogola et al. (34) reported that the WUE of maize was increased by application of nitrogen and Gao et al. (2004) [35] found that silicon, though not widely considered a plant nutrient, improves WUE in maize plants under water stress by reducing leaf transpiration and water flow rate in xylem vessels.
6. **Irrigation management** Approximately 40% of global agricultural output occurs on irrigated land, although only making up roughly 18% of total farmland [36] and two-thirds of the world's overall cultivation of wheat and rice (37). Better water transport, allocation, and distribution systems can enhance WUE (38) With the use of cutting-edge irrigation techniques, like as drip irrigation systems, which enable precise water delivery when and where it is required, may significantly minimise water losses. Different techniques have varying average application efficiencies: drip irrigation (75–90%), sprinkler irrigation (65–90%), and surface (flood) irrigation (60–90%) (39). Precision delivery methods encourage distribution homogeneity in the field, which is crucial for improving WUE. The irrigation schedule is made to make the best use of the water allotted, not always based on the total amount of water required by the crop. Optimising WUE for increased yields per unit of applied irrigation water can be achieved through the use of shortage (or regulated deficit) irrigation. For instance, the crop, maize, can withstand a certain amount of water stress for part of the growing season or the entire duration, yet yields are not significantly reduced (40). By providing water at crucial points in maize growth, finely textured soils like the vertosols found in Australia's northern grain belt are more likely to succeed with deficit irrigation. Kang et al. (2000a)[41] found that the best irrigation strategy for growing maize in a semi-arid region is to dry the soil during the seedling stage and then again at the stem-elongation stage. Other techniques to raise WUE include controlled alternate partial root-zone irrigation, which involves partially irrigating the root system while leaving the remaining portion exposed to drying soil, and alternate furrow irrigation, which involves alternating the irrigation of one of the two nearby furrows during successive waterings (42, 43).

**Emerging and Potential Opportunities for WUE**

Recent decades have seen significant investments in R&D initiatives and general technological advancements, which have produced new or developing potential for enhanced WUE in irrigated agriculture. This has taken the shape of more sophisticated and modern tools and methods in addition to less expensive and more precise substitutes.

#### **Remote Sensing -** Optimising the time and amount of irrigation applications improves WUE in irrigated agriculture. Whether plant, soil, or meteorological (evapotranspiration) based, the scheduling techniques discussed are often applied on the ground. These procedures are typically costly, labour-intensive, and difficult to automate [[**43**](https://www.mdpi.com/2073-4441/10/12/1771#B16-water-10-01771)], and mostly site-specific, making them unsuitable for usage in broad regions. Although remote sensing is not a novel concept in agriculture, it has become a focus of irrigation water management research in recent years because of its benefits, which include systematic measurements over time and space, the capacity to cover large areas, and the ability to be integrated into models and Geographic Information Systems (GIS).

There are growing new methods that use remotely sensed data to predict the water condition of crops or plants and, consequently, programme irrigations. The first is satellite imaging, which is used in several agricultural applications, such as tracking disease and production.

Across the last several decades, techniques for estimating evapotranspiration (ET) across vast areas have arisen that use algorithms to calculate vegetation indices from satellite data in conjunction with ground-based observations [[**44**](https://www.mdpi.com/2073-4441/10/12/1771#B21-water-10-01771),[**45**](https://www.mdpi.com/2073-4441/10/12/1771#B28-water-10-01771)].

The monitoring, assessment, and control of irrigation water consumption are not fully using remote sensing because of a number of problems, including one-time/one-place syndrome, quality of data, and spatial and temporal resolution. On the other hand, the current Lansat-8 satellite series can evaluate crop water usage and real crop evapotranspiration at the field and farm size because of its 30 m spatial resolution.

There are a number of commercial satellites now available that may be used for agricultural purposes, for instance ~~Sentinel-2 (~~[**~~https://sentinel.esa.int/web/sentinel/missions/sentinel-2~~**](https://sentinel.esa.int/web/sentinel/missions/sentinel-2)~~) and Planet (~~[**~~https://www.planet.com/markets/monitoring-for-precision-agriculture/~~**](https://www.planet.com/markets/monitoring-for-precision-agriculture/)~~).~~

An additional remote sensing method for assessing crop water status is being researched and involves utilising thermal and multispectral pictures obtained by drones or unmanned aerial vehicles (UAVs). Studies have demonstrated that the temperature of the plant canopy has a correlation with the water status of the plant, making it useful for managing irrigation water [[**46**](https://www.mdpi.com/2073-4441/10/12/1771#B31-water-10-01771)]. Cozzolino describes applications that use the electromagnetic spectrum's near- and mid-infrared reflectance to measure the water status of cereal crops, fruit trees, grapevines, and pastures [[**47**](https://www.mdpi.com/2073-4441/10/12/1771#B31-water-10-01771)].

The primary benefit of using remote sensing is its capacity to assess crop water status across large geographical scales, an ability that is not achievable with traditional approaches like soil sensors or plant-based procedures. It is also anticipated that when drone technology becomes more widely used, its costs will drop and many farmers would be able to afford it.

#### To optimise economies of scale, however, further work is also required to connect remote sensors and irrigators. Future very high resolution (<10 m) data collection using hyperspectral sensors, like the commercial IKONOS and Quick bird satellites currently in operation, fast data access being available of data from multiple sensors with a wide range of spatial, spectral, and radiometric features, and multi-data synthesis for remote sensing via streaming technology are some of the key opportunities and advancements to keep an eye on.

#### **2.Sensor and Communication Networks**

In order to enhance agricultural management, sensors are devices that gather a variety of data, including soil moisture and meteorological conditions. Soil moisture probes and weather stations are common types of sensors used in irrigation water management. In the past, agricultural or soil water monitoring devices were connected by cables, needed human data entry, and scheduled irrigations based on the collected information. In addition to the errors that occur when historical data is used for water management in the future, these manual processes are costly and time-consuming. In irrigated agriculture, the use of wireless sensor technology to enhance WUE is growing.

In the field, a number of wireless sensors are often utilised to track many variables, such as soil moisture and meteorological information. This is particularly motivated by the fact that competition and recent technological advancements have made inexpensive sensors more accessible. A hub or sink node to collect and process data from the sensor nodes, a number of individual instruments (sensor nodes), and a communication technology make up a wireless sensor network [[**47**](https://www.mdpi.com/2073-4441/10/12/1771#B32-water-10-01771)]. Actuators that may be utilised for regulating the irrigation system may also be present in the sensor networks.   
Numerous books address the application of wireless communication technology in agriculture, especially water management for instance Rehman et al. [[**47**](https://www.mdpi.com/2073-4441/10/12/1771#B32-water-10-01771)]. In agricultural nowadays, communication technologies including Bluetooth, WiFi, GPRS, LoRa, SigFox, and Long Range Radio (LoRa) are utilised [48]. For irrigation water management, ZigBee technology is frequently chosen because to its dependability, low cost, energy efficiency, and range [47,48].

Reference describes the usage of wireless sensors that collect data over the 3G internet network and assess soil moisture, temperature, and humidity [[**49**](https://www.mdpi.com/2073-4441/10/12/1771#B35-water-10-01771)]. Higher WUE may be attained by controlling the irrigation system in real time thanks to the automation of this vital data collecting process.

**WATER USE EFFICIENCY TRENDS**

Basso and Ritchie (2018)[50] suggested that Grain yields have grown throughout time, but water usage has stayed mostly steady, hence WUE has increased. Nagore et al. (2017)[51] contrasted newly released maize hybrids to an older hybrid, finding that the latter had a WUE of 23.1 kg ha−1 mm−1, whereas the former had a WUE of 25.1 kg ha−1 mm−1. During the course of this investigation, the more recent hybrids also shown a higher advantage in WUE at all soil water contents. The number of kernels per plant was the plant parameter that demonstrated the benefit of raising WUE. The newer genetic material will have a higher WUE due to its resistance to environmental stressors like water and temperature. There are two ways that climate change will increase WUE. First, the ability to recognise genotypes that, in the presence of temperature and water deficiency stress, have high absorption rates.

Many methods may be applied at the leaf and canopy levels, and creating instruments focused on phenotypic screening in relation to WUE would be beneficial for increasing our understanding. Quantifying the variations in plant responses to above-optimal temperatures, water shortages, and rising CO2 levels—and, more crucially, the relationships between these three variables—remains a formidable task. Secondly, it is important to acknowledge that various management strategies may be implemented to decrease soil water evaporation and redirect crop water consumption towards transpiration. This would minimise plant exposure to water-deficit stress and sustain maximum output.

By comprehending the physical and biological elements that combine to produce a high WUE, we can adapt to climate change.

Table 1 : Nitrogen and irrigation effects on water use efficiency (kg grain ha-1 mm-1) and N-use efficiency (kg grain (kg fertilizer N)-1) in wheat at Ludhiana, India (adapted from Gajri et al., 1993)[52].

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Irrigation(mm) | Water Use Efficiency  N rate(kg/ha) | | | | N use efficiency  N rate(kg/ha) | | |
|  | 0 | 40 | 80 | 120 | 40 | 80 | 120 |
| No irrigation(rain-fed) | 2.8 | 4.4 | 6.3 | 3.6 | 5.3 | 4.8 | 0.9 |
| 50 | 5.2 | 9.4 | 10.3 | 10.9 | 23.3 | 12.0 | 9.8 |
| 120 | 5.7 | 8.4 | 10.3 | 9.0 | 23.0 | 17.6 | 8.8 |
| 300 | 5.1 | 7.0 | 8.6 | 8.8 | 19.5 | 20.0 | 14.8 |

**CONCLUSION**

The initial definition of "water-use efficiency" has been significantly expanded over the past 50 years to include "crop productivity or value per drop of water." It refers, in the widest sense, to the overall socio-economic and environmental gains made possible by the use of water in agriculture. The more widely accepted idea of "water productivity" and its assessment across several scales provides a reliable indicator of how well agricultural systems use water to produce food. When compared to other resources used in production, water is more limited, hence increasing water productivity is more crucial.

Up to a certain amount, an increase in water supply boosts water productivity; however, it also enhances fertilizer-use efficiency by making applied nutrients more readily available. As the scope of interest expands from crop-plant to field, farm, system, basin, region, and national level, the complexity of measuring physical or economic water productivity rises. It is crucial to understand that the amount of water added to a field or agricultural system does not equal the amount of water utilised or exhausted for crop production. This is because water added to the system but not utilised is accessible downstream and is thus not included in the estimation. In addition to the traditional techniques, the utilisation of crop modelling and remote-sensing satellite data has made it possible to map the differences in water productivity at the basin or regional level in a comprehensive manner and to pinpoint possible regions for relevant interventions.

Enhancing a plant's water uptake efficiency and adaptability to decreased water supply are top priorities for scientists. In the end, 95% of all gaseous exchanges between the leaf and its surroundings are regulated by stomata. Thus, stomata are an ideal target for modifications meant for reducing water loss. Since stomata also control CO2 entry to the leaf's photosynthetic regions, achieving this objective will provide a challenge without reducing carbon gain (Lawson et al., 2012)[52]. Crucially, any modifications made to stomatal function, sensitivity, or responsiveness must not increase the plants' susceptibility to biotic stressors or harsh climatic conditions. More knowledge regarding the quantitative kinetics, particularly of signal transduction, will be beneficial since progress towards these goals is most likely to come from combining physiological and molecular genetic techniques with quantitative systems analysis techniques.

There are two ways that climate change will increase WUE. First, the ability to recognise genotypes that, in the presence of temperature and water deficiency stress, have high absorption rates. Many methods may be applied at the leaf and canopy levels, and creating instruments focused on phenotypic screening in relation to WUE would be beneficial for increasing our understanding.

Quantifying the variations in plant responses to above-optimal temperatures, water shortages, and rising CO2 levels—and, more crucially, the relationships between these three variables—remains a formidable task. Secondly, it is important to acknowledge that various management strategies may be implemented to decrease soil water evaporation and redirect crop water consumption towards transpiration. This would minimise plant exposure to water-deficit stress and sustain maximum output. By comprehending the physical and biological elements that combine to produce a high WUE, we can adapt to climate change.

**REFERENCES**

1. Thenkabail, P.S.; Hanjra, M.A.; Dheeravath, V.; Gumma, M. Global Croplands and Their Water Use from

Remote Sensing and Nonremote Sensing Perspectives. In Advances in Environmental Remote Sensing-Sensors,

Algorithms, and Applications; Weng, Q., Ed.; CRC Press: Boca Raton, FL, USA, 2011.

1. ABS. Water Use on Australian Farms; Australian Bureau of Statistics (ABS): Canberra, Australia, 2018.
2. Qureshi, M.E.; Grafton, R.Q.; Kirby, M.; Hanjra, M.A. Understanding irrigation water use efficiency at different scales for better policy reform: A case study of the Murray-Darling Basin, Australia. Water Policy 2011, 13, 1–17.
3. Passioura,J., 2006. Increasing crop productivity when water is scarce-from breeding to field management. Agric. Water Manage., 80:176-196
4. J.L. Araus, The problems of sustainable water use in the Mediterranean and research requirements for agriculture, Ann. Appl. Biol. 144 (2004) 259–272.
5. [2] X.P. Deng, L. Shan, H. Zhang, N.C. Turner, Improving agricultural water use efficiency in arid and semiarid areas of China, Agric. Water Manag. 80 (2006) 23–40.
6. S. Geerts, N. Raes, Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas, Agric. Water Manag. 96 (2009) 1275–1284.
7. N. Katerji, M. Mastrorilli, G. Ranab, Water use efficiency of crops cultivated in the Mediterranean region: review and analysis, Eur. J. Agron. 28 (2008) 493–507.
8. J.I.L. Morison, N.R. Baker, P.M. Mullineaux, W.J. Davies, improving water use in crop production, Philos. T. R. Soc, B363 (2008) 639–658.
9. Flexas J, Niinemets U, Galle A, Barbour MM, Centritto M et al. **2013**. Diffusional conductances to CO2 as a target for increasing photosynthesis and photosynthetic water-use efficiency. *Photosynth. Res.* 117:1–345–59
10. Brugière N, Zhang W, Xu Q, Scolaro EJ, Lu C et al. **2017**. Overexpression of RING domain E3 ligase ZmXerico1 confers drought tolerance through regulation of ABA homeostasis. *Plant Physiol* 175:31350–69
11. Sinclair TR, Tanner CB, Bennett JM **1984**. Water-use efficiency in crop production. *BioScience* 34:136–40
12. Osmond CB, Björkman O, Anderson DJ. 1980. Physiological Processes in Plant Ecology. Toward a Synthesis with Atriplex. Berlin: Springer
13. Flexas J, Niinemets U, Galle A, Barbour MM, Centritto M, et al. 2013. Diffusional conductances to CO2 as a target for increasing photosynthesis and photosynthetic water-use efficiency. Photosynth. Res. 117(1–3):45–59
14. Kolbe AR, Cousins AB. 2018. Mesophyll conductance in Zea mays responds transiently to CO2 availability: implications for transpiration efficiency in C4 crops. New Phytol. 217(4):1463–74
15. Expósito, A.; Berbel, J. Microeconomics of deficit irrigation and subjective water response function for intensive olive groves. Water 2016, 8, 254.
16. Heisey PW, Edmeades GO (1999) Maize production in drought-stressed environments: technical options and researchresource allocation, World Maize Facts and Trends 1997/1998
17. Birch CJ, Stephen K, McLean G Hammer GL and Robertson MJ (2006). Assessment of reliability of short to mid-season maizeproduction in areas of variable rainfall in Queensland (these proceedings)
18. Robertson MJ, Cawthray S, Birch C, Bidstrup R, Crawford M, Dalgleish NP, Hammer GL (2003) Managing the risk of growingdryland maize in the northern region. pp 112-119 in Birch, C. J. and Wilson, S. R. (Eds.) Versatile Maize, Golden Opportuni-ties, Proceedings, 5th Australian Maize Conference, 18-20 February 2003, tToowoomba, Australia, Maize Association ofAustralia, Darlington Point, NSW
19. Madhiyazhagan R (2005). Modelling approach to assess the impact of high temperature and water stress on dryland maize.PhD Thesis, The University of Queensland, 2005.
20. Titi AE (2003) ‘Soil Tillage in Agroecosystems’. (CRC Press)
21. Derpsch R (2001) Conservation tillage, no-tillage and related technologies, in Proc. 1st World Congr. Consverv. Agric., Madrid,October 1-5, 2001 Conservation Agriculture. A Worldwide Challenge, Vol. I, 161-17
22. Reinbott TM, Conley SP, Blevins DG (2004) Tillage and cropping systems - No-tillage corn and grain sorghum response to covercrop and nitrogen fertilization. Agronomy Journal 96 (4), 1158-1163
23. Guzha AC (2004) Effects of tillage on soil microrelief, surface depression storage and soil water storage. Soil & TillageResearch 76 (2), 105-114
24. Hartkamp AD, White JW, Rossing WAH, van Ittersum MK, Bakker EJ, Rabbinge R (2004) Regional application of a croppingsystems simulation model: crop residue retention in maize production systems of Jalisco, Mexico. Agricultural Systems 82(2), 117-13
25. Unger PW, Stewart BA (1983) Soil management for efficient water use: an overview. In ‘Limitations to efficient water use incrop production’. (Eds HM Taylor, WR Jordan, TR Sinclair) pp. 419-460. (ASA, CSSA and SSSA: Madison, Wisconsin
26. Jalota SK and Prihar SS (1998) Reducing soil water evaporation with tillage and straw mulching, Iowa State University Press,Ames, IA
27. Gicheru P, Gachene C, Mbuvi J, Mare E (2004) Effects of soil management practices and tillage systems on surface soil waterconservation and crust formation on a sandy loam in semi-arid Kenya. Soil & Tillage Research 75 (2), 173-184
28. Rahman MA, Chikushi J, Saifizzaman M, Lauren JG (2005) Rice straw mulching and nitrogen response of no-till wheat followingrice in Bangladesh. Field Crops Research 91 (1), 71-81
29. Pramanik SC (1999) In-situ conservation of residual soil moisture through tillage and mulch for maize (Zea mays) in tropical BayIslands. Indian Journal of Agricultural Science 69 (4), 254-257
30. Fisher PD (1995) An alternative plastic mulching system for improved water management in dryland maize production. Agricul-tural Water Management 27 (2), 155-166
31. Jin MG, Zhang, RQ, Sun LF and Gao UF (1999) Temporal and spatial soil water management: a case study in the Heilonggangregion, P.R. China. Agricultural Water Management 42 (2), 173-187
32. Peterson GA, Westfall DG (2004) Managing precipitation use in sustainable dryland agroecosystems. Annals of Applied Biology144 (2), 127-138
33. Ogola JBO, Wheeler TR, Harris PM (2002) The water use efficiency of maize was increased by application of fertilizer N. FieldCrops Research 78 (2-3), 105-117
34. Gao XP, Zou CQ, Wang LJ, Zhang FS (2004) Silicon improves water use efficiency in maize plants, Journal of Plant Nutrition27 (8), 1457-1470
35. Gleick H (2000) The world’s water 2000-2001, Washington, D.C.: Island
36. NSWRosengrant W (2000) ‘Dealing with Water Scarcity in the Next Century’. (International Food Policy Research Institute: Washing-ton, D.C.)
37. Hamdy A, Ragab R, Scarascia-Mugnozza E (2003) Coping with water scarcity: Water saving and increasing water productivity.Irrigation and Drainage 52 (1), 3-20
38. Fairweather H, Austin N, Hope H (2003) Water use efficiency: an information package, Canberra, Land and Water Australia
39. Sepaskhah AR, Ghahraman B (2004) The effects of irrigation efficiency and uniformity coefficient on relative yield and profit fordeficit irrigation. Biosystems Engineering 87 (4), 495-507
40. Kang SZ, Shi WJ, Zhang JH (2000a) An improved water-use efficiency for maize grown under regulated deficit irrigation. FleldCrop Research 67 (3), 207-214
41. Kang SZ, Liang, ZS, Pan, YH, Shi PZ, Zhang J.H. (2000b) Alternate furrow irrigation for maize production in an arid area.Agricultural Water Management. 45 (3), 267-274
42. Jones, H.G. Irrigation scheduling: Advantages and pitfalls of plant-based methods. J. Exp. Bot. 2004, 55, 2427–2436.
43. Ahadi, R.; Samani, Z.; Skaggs, R. Evaluating on-farm irrigation efficiency across the watershed: A case study of New Mexico’s Lower Rio Grande Basin. Agric. Water Manag. 2013, 124, 52–57.
44. Nagler, P.L.; Glenn, E.P.; Nguyen, U.; Scott, R.L.; Doody, T. Estimating riparian and agricultural actual evapotranspiration by reference evapotranspiration and MODIS enhanced vegetation index. Remote Sens. 2013, 5, 3849–3871
45. Cozzolino, D. The role of near-infrared sensors to measure water relationships in crops and plants. Appl. Spectrosc. Rev. 2017, 52, 837–849
46. Rehman, A.U.; Abbasi, A.; Islam, N.; Shaikh, Z.A. A review of wireless sensors and networks’ applications in agriculture. Comput. Stand. Interfaces 2014, 36, 263–270.
47. Jawad, H.M.; Nordin, R.; Gharghan, S.K.; Jawad, A.M.; Ismail, M. Energy-efficient wireless sensor networks for precision agriculture: A review. Sensors 2017, 17, 1781. [
48. Ojha, T.; Misra, S.; Raghuwanshi, N.S. Wireless sensor networks for agriculture: The state-of-the-art in practice and future challenges. Comput. Electron. Agric. 2015, 118, 66–84
49. McCulloch, J.; McCarthy, P.; Guru, S.M.; Peng,W.; Hugo, D.; Terhorst, A.Wireless sensor network deployment for water use efficiency in irrigation. In Proceedings of the Workshop on Real-World Wireless Sensor Networks, Glasgow, Scotland, 1 April 2008; pp. 46–50.
50. Basso, B., and Ritchie, J. T. (2018). Evapotranspiration in high-yielding maize and under increased vapor pressure deficit in the US Midwest. Agric. Environ. Lett. 3:170039. doi: 10.2134/ael2017.11.0039
51. Gajri, P.R., Prihar, S.S., Arora, V.K. 1993. Interdependence of nitrogen and irrigation effects on growth and input-use efficiencies in wheat. Field Crops Research 31:71-86.
52. Nagore, M. L., Della Maggiora, A., Andrade, F. H., and Echarte, L. (2017). Water use efficiency for grain yield in an old and two more recent maize hybrids. Field Crops Res. 214, 185–193. doi: 10.1016/j.fcr.2017.09.013
53. Lawson, T., and Blatt, M. R. (2014). Stomatal size, speed, and responsiveness impact on photosynthesis and water use efficiency. Plant Physiol. 164, 1556–1570