Water use efficiency as an indicator of environmental impact of irrigated crops under subtropical conditions

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Abstract

Water use efficiency (WUE) is an indicator that integrates aspects related to environment, technology, economy and agronomy, so it has a potential to be used in the analyses of the sustainability in agriculture. The main goal of this research was to evaluate the WUE as an indicator of environmental impact for irrigated beans, under sub-tropical climate. The experiment was performed in the city of Campinas, state of São Paulo, Brazil. WUE was assessed in the bean crop sown in the field, under two planting densities: 14 plants m^{-2} and 28 plants m^{-2}. A third treatment, corresponding to a planting density of 25 plants m^{-2}, was performed in four lysimeters, under an optimized soil and water management that permitted a potential yield to the variety of bean evaluated. Evapotranspiration was measured along the cycle from the water balance and the WUE observed in the field was compared to that measured in the lysimeters, generating an efficiency index. The WUE did not differ statistically ($P < 0.05$) among the treatments, reaching 0.630 kg m^{-3}, 0.693 kg m^{-3} and 0.710 kg m^{-3} for 14, 28 and 25 plants m^{-2} treatments, respectively. These results lead to an efficiency of 88.7% and 97.6% for 14 and 28 plants m^{-2} treatments, respectively, demonstrating the sensitivity of this integrating parameter to soil, water and plant management practices under sub-tropical environmental conditions.
Keywords: water resources, bean, agriculture.

WIT Transactions on Ecology and The Environment, Vol 181, © 2014 WIT Press
www.witpress.com, ISSN 1743-3541 (on-line)
doi:10.2495/EID140391

1 Introduction

Environmental indicators have been used in diagnostics and prognostics to assess the environmental impact of human actions and natural phenomena, besides choosing mitigation measures. Such indicators are selected based on the potential impacts expected, incorporating physical, chemical and biological parameters, such as those investigated in the areas of urban remnants (Longo *et al.* [1]), in agricultural areas (Medeiros *et al.* [2]), in degraded areas (Ribeiro *et al.* [3]) and in polluted rivers (Medeiros *et al.* [4]) among others.

Considering irrigated agriculture, one of the main environmental impacts is related to the volume of freshwater withdrawn for the supply of crop water requirements. In countries like Brazil, with a significant irrigated area of 4.5 million hectares, irrigated agriculture constitutes the highest water demanding sector, reaching 72% of the freshwater flow actually consumed in this country (ANA [5]).

Despite the relative abundance of the water resources in Brazil there are conflicts among the irrigated agriculture, the industrial sector and the urban water supply in some regions, as the Parana Watershed, which concentrates 32% of the population and 6% of the surface water resources from Brazil (ANA [5]). This scenery justifies the development of agricultural practices, technologies and conservative techniques of water use for irrigated agriculture, in order to reduce its environmental impact.

In this context, the selection of indicators that can compose an assessment on the impact of agricultural production on the demand of water resources is of considerable importance. In a country with an economic profile like Brazil, which is a world leader in grain yield, an indicator that incorporates the effect of the factors that influence agricultural production and demand of water resources is the water use efficiency (WUE).

The water use efficiency (WUE) is the ratio between grain production and the volume of water used by the crop throughout its life cycle; one indicator to assess whether production is limited by water supply or other factors (Angus and van Herwaarden [6]).

Consequently, WUE constitutes one of the most appropriate parameters to assess the environmental performance of irrigated crops when considering the sustainable use of water. This is a very important indicator for regional water resources assessment and management in agriculture (Fang *et al.* [7]).

The increased water use efficiency is related to factors that affect the process of evapotranspiration by modifying the energy available, the availability of water throughout the soil profile and the rate of vapour exchange between the soil and the atmosphere (Hatfield *et al.* [8]). These factors include the climate and the natural resources management such as soil and water (Stone and Moreira [9], Efetha *et al.* [10], Fang *et al.* [7], Sidique *et al.* [11]), crop management (Medeiros *et al.* [12], Gao *et al.* [13], Fang *et al.* [7]), weed management (Sidique *et al.* [11]), nutrient management (Fang *et al.* [7], Hatfield *et al.* [8]), plant genotype (Gilbert *et al.* [14]), genetic improvement (Fang *et al.* [7]) among others.

Therefore the literature has shown that the management of natural resources, technology and agronomic has direct and indirect influences on the water use efficiency by crops and, consequently, the environmental impacts of irrigated agriculture.

Another unexplored aspect in literature refers to the determination of maximum or potential WUE for the tropical and subtropical environmental conditions, involving genetic material, natural resources and regionalized technology. This information takes on a meaningful importance to environmental management agencies and those related to food production, aiming the establishment of policies related to the food safety and the access to water from different sectors of society.

The aim of this study was to evaluate the water use efficiency (WUE) as an indicator of environmental impact for agriculture in subtropical environment, using the irrigated bean crops as a bio indicator, seeded at different densities.

2 Material and methods

This research was carried out at the Núcleo Experimental de Campinas (NEC) of Instituto Agronômico (IAC), Campinas city, state of São Paulo, Brazil, located at the latitude 22°52’ S, longitude 47°04’ W, 600 m above mean sea level.

The soil of the experimental area is an oxisoil, known as red Latosol by the Brazilian System of Soil Classification (Embrapa [15]), clay texture (61% clay), naturally well drained.

The accumulated rainfall reached 181 mm during the whole season, but 49% (88.7 mm) occurred in the last week of the experiment, while the mean reference evapotranspiration estimated from Penman – Monteith method was 5.5 mm d^{-1}. These weather conditions do not allow an economic production of common beans (*Phaseolus vulgaris* L., cv. IAC – Carioca) without the use of irrigation.

IAC-Carioca varietal is a bush bean with indeterminate growth habit, less than 0.4 m depth of effective root system and the total duration of growth may vary from 90 to 95 days.

A completely randomized design was carried out with three treatments and four replications, as follow (Medeiros *et al.* [12]):

a) crop planted in four compensation lysimeters (Figure 1) with a constant groundwater table maintained at 0.45 m underground and 1.4 m^2 area as described by Medeiros and Arruda [16]. The crop population density was considered 25 plants m^{-2}.

b) crop sown with population densities of 14 and 28 plants m^{-2} in eight irrigated plots 13 x 13 m, inserted in 1.1 ha of irrigated field. Water was applied by sprinkler irrigation at weekly intervals, which did not allow water depletion corresponding to a soil tension of 60 kPa in the first 0.2 m depth.

Measurements of water balance components were carried out to estimate the actual evapotranspiration, which was calculated from eqn (1):

Figure 1: Bean crop sown on compensation lysimeters.

$$\Delta S = (P + I + U) - (R + D + Et) \tag{1}$$

where ΔS is the stored water in the root zone, P is the rainfall, I is the irrigation depth, U is the upward capillary flow into the root zone, R is the runoff, D is the downward drainage out of the root zone, Et is the evapotranspiration.

Crop yield was determined from the dry weight of the grains and the total dry matter measured from above ground biomass. Finally, the water use efficiency was calculated in two ways. The first was based on the seed yield (Hatfield *et al.* [8]) by eqn (2):

$$WUE = \frac{Y}{Et} \tag{2}$$

where WUE is the water use efficiency (kg m^{-3}), Y is the seed yield (g m^{-2}) and Et is the cumulative evapotranspiration (mm).

The second, from the above ground biomass of the crop (Hatfield *et al.* [8]), as the following eqn (3):

$$WUE_{DM} = \frac{DM}{Et} \tag{3}$$

where WUE_{DM} is the water use efficiency from biomass (kg m^{-3}), DM is the total dry matter of the bean plants (g m^{-2}) and Et is the cumulative evapotranspiration (mm).

The efficiency index for estimating the relative WUE was calculated by eqn (4) and eqn (5):

$$EI = 100\frac{WUE}{WUE_{max}} \tag{4}$$

where EI is the efficiency index (%), WUE is the water use efficiency (kg m^{-3}), WUE_{max} is the maximum water use efficiency, determined in the compensation lysimeters (kg m^{-3})

$$EI_{DM} = 100 \frac{WUE_{DM}}{WUE_{DM\,max}} \tag{5}$$

where EI is the efficiency index related to dry matter (%),WUE_{DM} is the water use efficiency from dry matter (kg m^{-3}), WUE_{DMmax} is the maximum water use efficiency from dry matter, determined in the compensation lysimeters (kg m^{-3})

3 Results and discussion

Environmental factors, water management and growth characteristic of the cultivar beans assessed promoted compensatory effects in the irrigated field treatments.

Seed yield reached 2,137 kg ha^{-1}, 2,253 kg ha^{-1} and 3,197 kg ha^{-1} for the treatments of 14, 28 and 25 plants m^{-2}, respectively. No significant difference ($P<0.05$) by Duncan test was observed among the treatments, as can be seen in Table 1, despite the difference in the planting density. This observation is probably due to the variability of the results obtained in the experimental plots.

Table 1: Evapotranspiration (Et), water use efficiency (WUE) based on seed yield (Seed) and total dry matter (DM) of the irrigated beans crop, and the efficiency index (EI).

Treatment	Et	Yield		WUE		EI	
		Seed	DM	Seed	DM	Seed	DM
plants m^{-2}	mm	----- g m^{-2} -----		---- kg m^{-3} ----		%	
14	339,0	213,7a	469,3a	0,630a	1,384a	88.7	81.8
28	325,0	225,3a	484,1a	0,693a	1,490a	97.6	88.1
25	451,4	319,7a	752,3a	0,710a	1,691a		

Means followed by the same letter do not differ by Duncan test at 5%.

The highest production was observed in the crop cultivated into compensation lysimeters, being 49.6% and 41.9% higher than that observed in the treatments 14 and 28 plants m^{-2}, respectively. This result observed in the lysimeters can be considered the maximum dry bean yield to this variety and the mesological conditions observed during the experiment.

Information related to maximum yield of crops, even under controlled water supplies is scarce in tropical and sub-tropical conditions. Periods of moderate water stress, soil compaction, insect infestation, weeds, diseases and other factors can affect the crop performance, under field condition, besides the difficulties inherent to the monitoring of water consumption by crops. All these unfavourable conditions make the lysimeters a precise and controlled methodology to measure the water consumption by crops.

Among the factors that contributed to the increased production of bean sown on compensation lysimeters, the uniform supply of water throughout the crop cycle must be highlighted, which enabled the maintenance of an average potential of soil water of -3.2 kPa at 0.10 m depth (Medeiros and Arruda [16]). This level of soil water tension is very difficult to maintain in the irrigated field under sprinkler system.

Comparing the yield of the treatments conducted under sprinkler irrigation it can be inferred that the less competition for water and solar radiation in the treatment of 14 plants m^{-2}, associated to the characteristic of the varietal bean, which presents indeterminate growth, influenced the results. These ecological factors led to a superior plant performance of the 14 plants m^{-2} treatment when compared to plant density treatment 28 plants m^{-2}, as observed by Medeiros *et al.* [12].

The results of the total dry matter followed the same trend observed in the seed production, that is, there were no significant differences ($P < 0.05$) among treatments.

In the field, the total dry matter production reached 4,693 and 4,841 kg ha^{-1} for the treatments 14 and 28 plants m^{-2} respectively, and 7,523 kg ha^{-1} for the crop sown in the compensation lysimeters. These results led to relative differences of 60.3% and 55.4% among treatments of 14 and 28 plants m^{-2} when compared to 25 plants m^{-2}, respectively.

Again, these relative differences were related to the growth characteristics of the varietal and the water management.

In the field, the bean crop has experienced periods of moderate water stress, which anticipated the senescence in relation to the crop sown in the lysimeters. Consequently, the green biomass at the end of the experiment was higher in the lysimeters.

The same analysis applies to the comparison of the total dry matter productions observed between irrigated treatments in the field. Although a treatment has only half the population density compared to the other, the relative difference in accumulated total dry matter was only 3.1%.

In the planting density of 14 plants m^{-2} the bean plants showed symptoms of senescence less accentuated with the attendance of a larger amount of green biomass in relation to the treatment of 28 plants m^{-2}, compensating the difference in the population of plants.

When assessing the relative differences in WUE and WUE_{DM} among the treatments much lower values were observed compared to that observed in the yield and total dry matter.

WUE reached 0.710 kg m^{-3} for the bean crops sown in the compensation lysimeters, which was higher than those observed in the treatments of 14 and 28 plants m^{-2} that achieved 0.630 kg m^{-3} and 0.693 kg m^{-3}, respectively, corresponding to a relative difference of 12.7% and 2.5%, respectively.

The WUE values are higher than that recorded by Doorenbos and Pruitt [17] for the bean, ranging from 0.30 to 0.60 kg m^{-3} for grain moisture of 10%.

Barros and Hanks [18] estimated WUE for bean, in the United States, which ranged from 0.65 kg m^{-3} to 0.75 kg m^{-3}, given the variation in crop residue and irrigation management. In Canada, Efetha *et al.* [10] found WUE ranged from 0.74 to 1.90 kg m^{-3} for beans.

In WUE_{DM} estimates, it was found that the relative difference between treatments increased. In absolute terms, the values of WUE_{DM} reached 1.384 kg m^{-3}, 1.490 kg m^{-3} and 1.691 kg m^{-3} for the treatment of 14 plants m^{-2}, 28 plants m^{-2} and 25 plants m^{-2}, respectively. The best performance was observed in the crop sown in the compensation lysimeters, which was higher 22.2% and 13.5% when compared to the beans planted under the population of 14 and 28 plants m^{-2}, respectively.

There is a larger scarcity of results related to WUE_{DM} for beans in the literature; one important example is Barros and Hanks [18] that estimated a range varying from 1.17 to 1.41 kg m^{-3}, which is lower in relation to the findings of this research.

Therefore, WUE and WUE_{DM} values achieved in this study are within the range found in other experiments related to irrigated beans. However, the comparison of WUE and WUE_{DM} results from different bibliographic sources presents some limitations due to the variability of the cultivars, soil management, irrigation management, agronomic practices, climate etc.

Based on the results of the efficiency index for WUE, related to the economic yield of the crop, one observes the best performance of bean sown at 28 plants m^{-2} in relation to the treatment of lower seeding rate. In this treatment the period of moderate water stress decreased the production, but provided a lower water consumption, which increased the value of WUE. The same tendency was observed in the EI_{DM}, where 28 plants m^{-2} presented the best performance.

Price charged from irrigators for the water in the Piracicaba River Basin, where this study took place, has a value of U.S. $4.55 per 1000 m^3, in 2013.

Based on this value, estimates from cost of water per hectare for the 14, 28 and 25 plants m^{-2} treatments reach U.S. $15.40, U.S. $14.78 and U.S. $20.50 respectively.

Considering that the sale price of the common bean in October 2013 reached U.S. $0.98 kg^{-1}, the gross revenue would achieve U.S. $2,094.26, U.S. $2,207.94 and U.S. $3,133.10 per ha to the 14, 28 and 25 plants m^{-2} treatments respectively.

Consequently, the water cost would represent 0.74%, 0.67% and 0.65% of the value of bean yield per hectare in the treatments 14, 28 and 25 plants m^{-2}, respectively. This information allows evaluating the impact of the water cost on the crop management, associated to WUE.

Therefore, WUE is an indicator that incorporated the economic and environmental performance of the crop, as can be seen in this work.

Kadyampakeni *et al.* [19] have also used WUE in the analysis of social-economic aspects in the water management of beans, in Malawi, Africa, showing the adequacy of this indicator to evaluate the sustainability of the irrigated agriculture.

4 Conclusions

The results revealed that WUE was a sensitive parameter for changes in the management of water resources, soil and plant, being an indicator of the sustainability of agricultural production and conservation of natural resources, especially the water.

Acknowledgements

The authors thank the Pro Reitoria de Pesquisa, from Universidade Estadual Campinas (UNICAMP), from São Paulo state, Brazil for the financial support.

The authors also thank the Instituto Agronômico from São Paulo state (IAC), Brazil for the financial and technical support.

Finally the authors thank the following researchers and professors for their scientific contributions: Emilio Sakai (IAC); Mamor Fujiwara (IAC); Regina Célia Matos Pires (IAC) and Newton Roberto Boni (UNICAMP – *in memoriam*).

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