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Impact of improving water-use efficiency on its valuation: The case of irrigated wheat production in Tunisia

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Abstract

The main objectives of this study are to evaluate the impact of irrigation water use efficiency improvement on enhancing the value of water used for irrigation; and to estimate the potential for private water cost reductions in irrigated durum wheat production systems of semi-arid Tunisia. Data Envelopment Analysis and stochastic frontier methods were combined for this aim. Results show that significant inefficiencies exist in the farm sample under investigation. We also show that increasing irrigation water use efficiency could shift the curve of marginal water value upwards, thereby indicating a rising of water value. By operating at full water economic efficiency level, farms would be able to reduce water costs for wheat production by about 42%, in average. We conclude that there is a wide scope to improve water use efficiency in the study area, allowing for a better valuation of the water resources used for the irrigation.

Key words: water use efficiency; data envelopment analysis; stochastic frontier production function; water value; durum wheat production; Central Tunisia

1. Introduction

The cereal sector is considered to be highly strategic in Tunisia. It provides major staple food commodities for most Tunisian households. Cereals are cultivated on almost one third of agricultural land (1.5 million hectares) and generate 13% of the total agricultural value added. However, cereal productivity remains very low compared to its potential. The current average yield per hectare of cereals in Tunisia is below 1.3 tons/ha (Ministry of Agriculture 2012). This is why importation is usually required in Tunisia each year in order to meet the domestic demand, of approximately three million tons (Institut National de Statistique 2010). Improvement in cereal productivity in Tunisia became an obligation for policy makers, who need to reduce the dependence on the importation of this commodity.

Among cereals in Tunisia, wheat is the most important in terms of its output and cultivated area. It occupies about 50% of all areas under cereals (800 000 ha on average) and represents almost 55% of the total cereal production (Ministry of Agriculture 2012). Currently, the irrigated wheat area is around 80 000 ha (Ministry of Agriculture 2011). This sub-sector faces a lot of challenges, such as the sustainability of the cultivated areas, the limited water resources for irrigation, and the arid climate, which is characterised by frequent drought. The use of irrigation, when water is available, is proposed as a main solution for yield improvement. In this context, emphasis was on the extension and development of irrigated areas as an alternative to achieving this goal. Although the area of irrigated wheat increased from 47 500 ha in 1998 to 80 000 ha in 2012 (Ministry of Agriculture 2012), wheat yield in irrigated areas has remained stable, at around 3.8 tons/ha, since the 1990s (Institut National des Grandes Cultures 2012). However, there is limited scope in Tunisia for a further increase in the use of land and water resources in order to increase cereal production. In fact, fresh water mobilisation has reached its limit. Therefore, future increases in irrigated wheat production have to be achieved by enhancing productivity. Most studies related to water-use efficiency in Tunisia show that water is still used inefficiently at the farm level (Albouchi *et al.* 2007; Dhehibi *et al.* 2007; Frija *et al.* 2009; Chemak *et al.* 2010; Chemak & Dhehibi 2010; Chebil *et al.* 2012; 2013). Low irrigation efficiency is associated with technical and allocative inefficiencies. This is controversial in the current situation in Tunisia, where water scarcity is accruing. The water price is heavily subsidised and there is little or no incentive to economise this resource, implying pointing to the tendency of farmers to over-irrigate their crops. The growing scarcity and rising cost of water have led to the realisation that water has to be allocated and used more efficiently. If the price of water is below its real cost, it will be used inefficiently.

The main objectives of this study were to evaluate the impact of an improvement in water-use efficiency on the valorisation of irrigation water, and to estimate the potential of a reduction in water cost in durum wheat production in central Tunisia. This was done through an innovative combination of existing methodological approaches – data envelopment analysis (DEA) and the stochastic frontier production function.

The remainder of this paper is organised into six sections. First, we present the conceptual framework adopted in this study, followed by the methodology and data. The results and discussion come next. The conclusions and policy implications of the study are presented in the last section.

2. Conceptual framework: Economic efficiency, water value and the production frontier

Economic efficiency is divided into technical and allocative efficiency. Technical efficiency (TE) can be defined as producing a maximum amount of output for a given set of inputs (output oriented), or producing a given level of output using a minimum level of inputs (input oriented). If the production frontier is known, the technical inefficiency of any particular firm can be assessed easily by simply comparing the position of the firm relative to the frontier (Coelli 1995). Allocative efficiency (AE) is reached when the value of marginal product (VMP) of each input equals its unitary cost (Farell 1957).

Technical and allocative inefficiency can be illustrated with the aid of Figure 1, using output (Y) and input (water). The production frontier for a firm using best practice techniques (efficient situation) is shown by frontier F. At points B and C, the firms are technically efficient (since they are located at the production frontier F), and there is no way to obtain more output without using more input. A firm operating at point C on the frontier that uses W* level of water and receives a profit of max $\pi(C)$, where the iso-profit line is tangential to its production frontier, is economically efficient. On the other hand, a firm operating at point B on frontier F uses W_i level of water and receives lower profits – $\pi(B)$ – than firm C. This profit loss is due to allocative inefficiencies.

However, firms do not operate at their best practices output, curve F, but rather at a lower frontier F' (current situation). At point A, the firm experiences both allocative and technical inefficiency. A movement to point production at B would leave the firm technically efficient, but still inefficient from an allocative perspective, as profit could be raised further to level C. In terms of profit loss, a firm operating at point A experiences a shortfall in profit, given by $\pi(C) - \pi(A)$. Of this total shortfall, $\pi(B) - \pi(A)$ is attributable to technical inefficiency, and $\pi(C) - \pi(B)$ is attributable to allocative inefficiency.

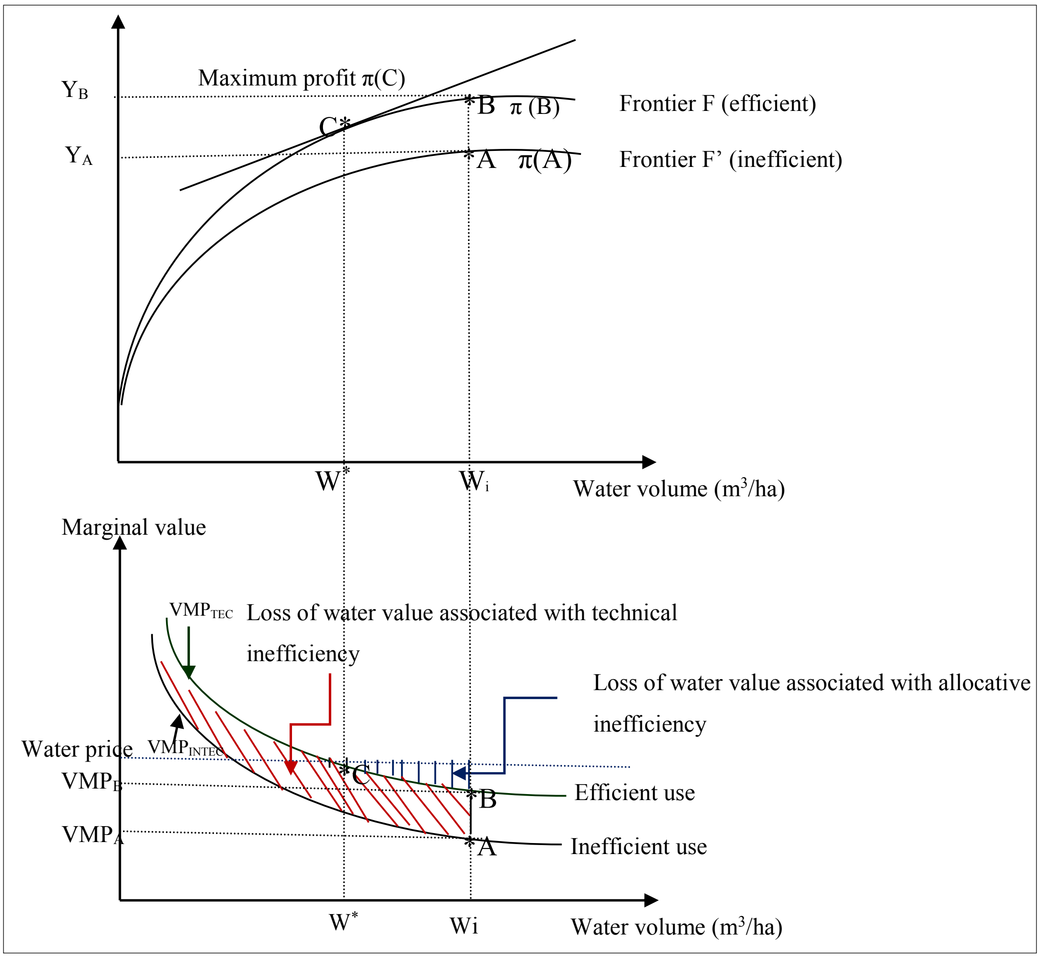

Figure 1: Technical, allocative inefficiency and marginal water value
Source: Own elaboration

The curves of marginal water value for inefficient water use (VMP_{INTEC}) and enhanced efficient water use (VMP_{TEC}) are illustrated in Figure 1. The difference between the marginal water values in the two situations is equal to the loss of water value associated with the technical inefficiency. However, the allocative inefficiency is given by the difference between the marginal value of water and the price of water. The economic efficiency (EE) of one input (water) is decomposed into two components: TE and water allocative efficiency (WAE) (Coelli *et al.* 2007). All these efficiency measures take a value ranging from zero to one. Water EE is determined by multiplying TE and WAE (EE = TE*WAE).

3. Methodology

The methods of analysis used in this study are DEA and the stochastic frontier production function (Cobb Douglas).

3.1 Data envelopment analysis (DEA)

The DEA models have frequently been applied in agriculture due to their advantages. Charnes, Cooper and Rhodes (CCR) (Charnes *et al.* 1978) proposed a model that had an input orientation and assumed constant returns to scale (CRS). Banker, Charnes and Cooper (BCC) (Banker *et al.* 1984) suggested an extension of the CRS DEA model to account for variable returns to scale (VRS) situations. The use of the CRS specification when not all farms are operating at the optimal scale will result in measures of TE that are confounded by scale efficiencies (SE).

In the present analysis we used an input-oriented DEA model, where the estimated efficiency scores typically indicate how much a farm should be able to reduce the use of its all inputs compared to the best performers.

Suppose data on K inputs and M outputs for each of the N farms. For farm *i*, input and output data are represented by the column vectors x_i and y_i respectively. The *KxN* input matrix *X*, and the *MxN* output matrix *Y*, represent the data for all *N* farms in the sample. The DEA model to calculate the TE is given by equation (1), namely the input-oriented formulation of the BCC model can be represented as follows:

$$Min_{\theta\lambda}\theta, \quad \text{subject to} \quad \begin{array}{l} -y_i + Y\lambda \geq 0, \\ \theta x_i - X\lambda \geq 0, \\ N1'\lambda = 1, \\ \lambda \geq 0 \end{array} \tag{1}$$

with θ being a scalar, *N*1 a vector of ones, and λ an N*1 vector of constants. This model is solved for each farm once in order to obtain a value for θ. This value, between zero and one, is the TE score for farm *i*. It should also be noted that equation (1) has a VRS specification that includes a convexity constraint ($N1'\lambda = 1$). Without that constraint (CCR model), equation (1) represents a CRS specification that assumes that farms are operating at their optimal scale. A measure for scale efficiency is given by dividing the technical efficiency score under the CRS specification by the efficiency score under the VRS specification ($SE = TE_{CRS} / TE_{VRS}$). That is, the CRS technical efficiency measure is decomposed into pure TE and SE.

3.2 Stochastic production frontier

The Cobb-Douglass stochastic production frontier is used for the empirical analysis. It is given by equation (2):

$$Y_i = A.W_i^{\beta_0} \prod_{k=1}^{k} X_{ki}^{\beta_k} e^{\varepsilon_i} \tag{2}$$

where Y_i is the output of the *i*th farm, A is the intercept, W_i is the volume of supplied water (rain + irrigation), X_{ki} is the *k*th input, and $\beta_o, \ldots\ldots \beta_k$, are the coefficients for water and the other inputs respectively. The error term, ε_i, of the model is composed of two independent elements (Aigner *et al.* 1977):

$$\varepsilon_i = v_i - \mu_i \tag{3}$$

where v_i is the symmetric disturbances assumed to be identically, independently and normally distributed as N(0, σ_v^2); μ_i is a one-sided component, and $\mu_i \geq 0$ reflects technical efficiency relative to the stochastic frontier. It is assumed that μ_i is a half-normal distribution N(0, σ_u^2). The maximum likelihood estimation for equation (2) provides estimators for β and variance parameters $\sigma^2 = \sigma_v^2 + \sigma_u^2$, as well as $\gamma = \frac{\sigma_u^2}{\sigma^2}$.

The coefficient β_o can be considered as the output elasticity of the water variable. The marginal production value for water can be written as follows, where the marginal water value estimated as the variation of the output value due to a given change of the water use:

$$VMP_w = P_Y \frac{\partial Y}{\partial W} \tag{4}$$

where P_Y is the unit price of the output.

Allocative efficiency is determined by comparing the VMP_W with the market price of water (P_W). If $VMP_W > P_W$, water is underused and farm profits can be raised by increasing the use of water. If, inversely, $VMP_W < P_W$, the water is overused and its use should be reduced to raise farm profits. The point of allocative efficiency (and maximum profit) is reached when $VMP_W = P_W$.

4. Study region, data and definition of variables

The current study was undertaken in the district of Chebika, which is located in the governorate of Kairouan (centre of Tunisia). This region is characterised by a high number of cereal farms. Cereals occupy 16 920 ha in Chebika and represent 33% of the total agricultural area. Of this area, 12 750 ha is rain fed and 4 170 ha is irrigated. Irrigated cereals, despite being planted in limited areas (24.6% of area under cereals), provide the largest share of cereal production in Chebika (63.7%). It is important to note that the district of Chebika is the largest producer of irrigated cereal in the governorate of Kairouan (Cellule Technique de Vulgarisation 2012). Chebika is also facing growing problems relating to water scarcity. It is located in the semi-arid bioclimatic lower floor and characterised by moderate winters. The rainfall during the growing season of 2010/2011 was 290 mm. Groundwater represents the main water source.

The data used in this study was collected from 170 Tunisian wheat farmers who cultivated irrigated durum wheat during the agricultural season 2010/2011. The total number of wheat farmers in the district of Chebika was 1 021, which means that our sample is representative. The sample used was stratified per area, and farmers were selected randomly in each of these areas. The survey was conducted in 2012, and farmers were selected with the collaboration of the extension service in the region.

Wheat production value per ha was used as output, along with five inputs, viz. water (W), seeds (S), chemical fertiliser (F), labour (L) and machinery (M), were used in the estimation of the production function and DEA model. Elements of descriptive statistics relating to inputs, outputs and farm-specific variables are presented in Table 1. The volume of irrigation water applied per hectare varies between farmers. It ranges from 500 m^3/ha to 6 000 m^3/ha. The sample average was 2 700 m^3/ha. The average production value per ha in our sample was equal to 2 226.26 TND, corresponding to an average yield of 3.9 tons/ha.

Table 1: Summary statistics of the variables used in the analysis of efficiency

Variable		Mean	SD	Min	Max
Output	Output value (TND/ha)	2 226.26	636.46	1 016.00	4 370.00
Inputs	Applied water (m^3/ha)	2 696.24	1 110.80	500.00	6 000.00
	Seeds (TND/ha)	114.22	31.71	55.00	154.00
	Chemical fertiliser (TND/ha)	142.23	60.02	33.00	338.00
	Labour (TND/ha)	66.46	22.30	31.50	178.75
	Machinery (TND/ha)	378.26	117.41	165.00	1 300.00
Farm-specific factors	Age (years)	50.43	13.19	22.01	86.00
	Education level (1 if farmer has more than secondary level, 0 otherwise)	0.27	0.44	0	1
	Experience (years)	25.78	13.05	2.00	60.00
	Size (total cropping area in ha)	14.01	13.34	1.20	95.00
	Water source (1 if the farmer uses two sources, 0 if one)	0.04	0.19	0	1
	WUA (1 if farmer is member, 0 otherwise)	0.36	0.48	0	1
	Irrigation management (1 if farmer respects the critical period, 0 otherwise)	0.37	0.49	0	1
	Wheat variety (1 if farmer uses Maali variety, 0 otherwise)	0.35	0.48	0	1
	Pesticide (1 if farmer uses pesticide, 0 if not)	0.42	0.49	0	1

5. Empirical results

5.1 Efficiency scores result

The estimation of efficiency scores by the DEA was conducted using the DEAP (Data Envelopment Analysis Program) software (Coelli 1996). The distribution of the technical efficiency of cereal farms in the region is summarised in Table 2. Estimated efficiency measures reveal the existence of substantial TE of production in the sample of wheat farms at hand. The computed average technical efficiencies under CRS and VRS were 70.7% and 82.0% respectively. The average of SE is about 86.5%. The DEA results reveal a wide variation in individual efficiency scores across farms, ranging from 100% to 28.0%. Given the currently used technology (input levels), this suggests that farms in the sample are using 30% more inputs to produce the current level of output.

Table 2: Frequency distribution of technical efficiency estimates

	CRS	SE	VRS
TE ≤ 50 (%)	*5.9*	*0.6*	*0.6*
50 < TE ≤ 80 (%)	*71.8*	*31.7*	*42.9*
TE > 80 (%)	*22.3*	*67.7*	*56.5*
Mean (%)	**70.7**	**86.5**	**82.0**
Min (%)	**27.9**	**46.5**	**48.9**
Max (%)	**100**	**100**	**100**
Std. dev.	**14.9**	**13.1**	**13.6**

Under the CRS, the results indicate that 5.9% of farmers had technical efficiency scores that were less than or equal to 50%, 71.8% of them had efficiency scores of between 50% and 80%, and 23.3% of farms had a TE strictly greater than 80%. These results provide useful information about the heterogeneity of the farms' performance and the potential for increasing wheat production in the studied district.

5.2 Empirical estimation of stochastic production frontier

The parameters of the Cobb-Douglas stochastic production frontier were estimated using the Frontier 4.1 computer program (Coelli 1996). The results of the coefficients and related tests are shown in Table 3. The signs of the estimated parameters are as expected. For the majority of independent variables, the estimated coefficients were positive and statistically significant at the 5% level. The variance parameter of the model (γ) is significantly different from zero at the 5% level, which means that there are inefficiencies in the production.

Table 3: Maximum likelihood estimates of the stochastic production frontier

	Coefficients	**t-stat**
Constant	1.96	3.11***
Water	0.27	3.98***
Seeds	0.15	1.78*
Fertilisers	0.12	2.70***
Labour	0.16	2.18*
Machinery	0.27	2.77***
σ^2	0.08	5.69***
γ	0.75	8.32***
Log-likelihood	32.31	
Observations	170	

Note: ***, **, * indicate significance at the 1%, 5% and 10% level respectively

Estimated partial production elasticities with respect to the production factors are indicated in Table 3. The value of these elasticities for water, seeds, chemical fertiliser, labour and machinery are 0.27, 0.15, 0.12, 0.16 and 0.27 respectively.

Using the estimated parameters of the production frontier, we calculated the marginal value of water applied to wheat production in the Chebika region. The marginal value of irrigation water varies according to the quantity of water applied, which is shown in Figure 2. This figure shows that VMP falls as the volume of applied water increases, which is consistent with the usual assumptions economists make regarding decreasing marginal physical product. The curve of the marginal water value in Figure 2 corresponds to the theoretical expectations, where the marginal value of water is negatively correlated with the volume of water applied.

The effects of technical efficiency on marginal values of water applied for irrigation are also illustrated in Figure 2. It should be noted that an improvement in technical efficiency could shift the VMP curve upwards, thereby raising VMP.

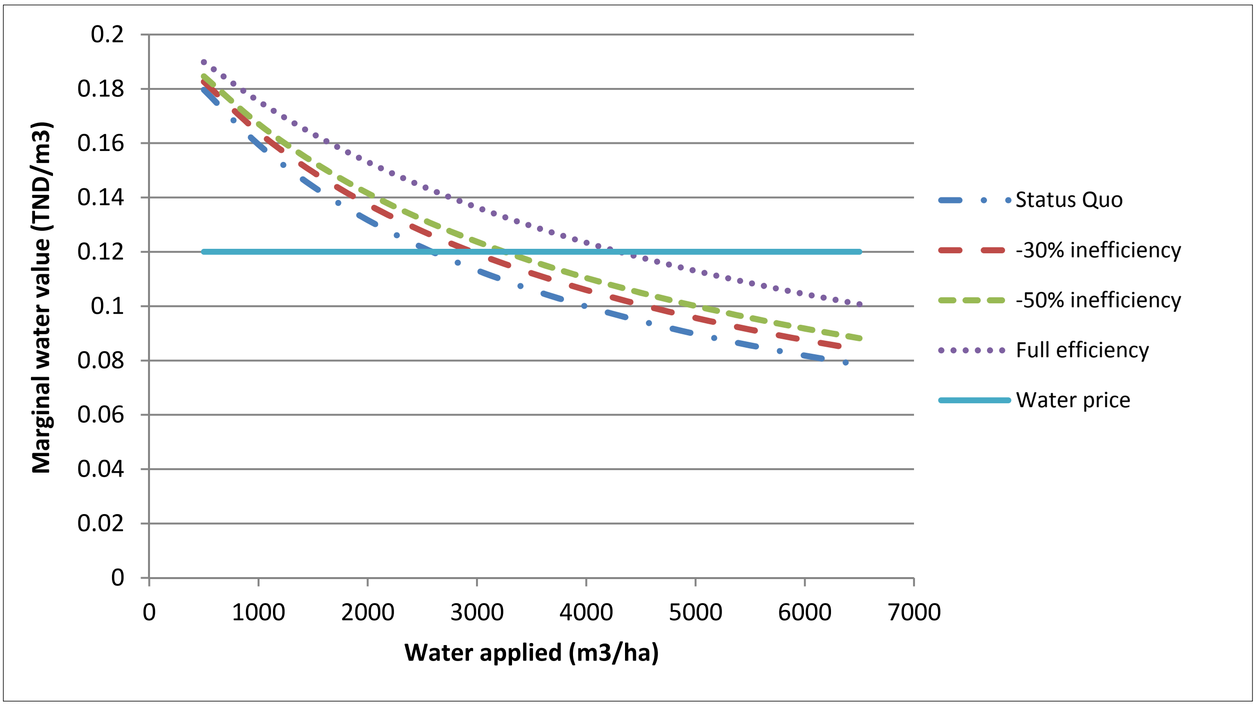

Figure 2: Curves of marginal water value under different scenarios of improving technical efficiency

The average water AE and EE are 81.58% and 58.08% respectively (Table 4). Thus, both results reveal substantial inefficiencies among the farms in Chebika. We note that 25.29% of farms have EE scores of less than 50%, while 67.65% have an efficiency score of between 50% and 80% and only 7.06% of farms have an EE greater than 80%.

Table 4. Frequency distribution of water AE and EE estimates

	AE	**EE**
TE ≤ 50 (%)	*1.18*	*25.29*
50 < TE ≤ 80 (%)	*37.64*	*67.65*
TE > 80 (%)	*61.18*	*7.06*
Mean (%)	*81.58*	*58.05*
Min (%)	*47.03*	*13.43*
Max (%)	*99.69*	*99.69*
Std. dev.	*10.82*	*15.14*

6. Discussion

The empirical results show that significant irrigation water-use inefficiencies in wheat production exist in our farm sample. This means that there always is a large potential to reduce water costs. Our results are in line with other case studies in Tunisia, which were interested in the calculation of water-use efficiency on irrigated farms (Albouchi *et al*. 2007; Dhehibi *et al*. 2007; Frija *et al*. 2009; Chemak *et al*. 2010; Chemak & Dhehibi 2010; Naceur *et al*. 2010; Chebil *et al*. 2012; Dhehibi *et al*. 2012; Chebil *et al*. 2013). Few authors have focused on measuring farms' technical efficiency in Tunisia (Bachta & Chebil 2002; Dhehibi *et al*. 2012; Chebil *et al*. 2013), and they have also found that there is a large potential to increase this efficiency indicator.

However, to our knowledge, no studies have focused on both water AE and EE. Our study confirms the possibilities of productivity gains by improving both the AE and EE of water. The potential for water cost reductions when a farm operates at its full efficient level is reported in Table 5. On average, farmers in our sample are able to reduce their current cost of water by 42% without harming their production level. TE and water AE levels account for about 61% and 39% of the total cost reductions respectively.

Table 5: Potential of water cost reductions in wheat production

	Observed cost	**Potential of water cost reductions at full efficiency levels**		
		Technical	Allocative	Total
Water cost (TND/ha)	296.60	75.95	48.47	124.43
% of the total		61.04	38.96	100

7. Conclusion and policy implications

This paper investigated the impact of improvements in water-use efficiency on water value and the potential of water cost reductions in durum wheat production in central Tunisia. The data envelopment analysis method, combined with a Cobb-Douglas production function, was used for this purpose.

The results show that significant inefficiencies exist in the investigated farm sample. The average technical efficiencies estimated under the constant returns to scale and variable returns to scale hypothesis of the farms in the sample were 70% and 82% respectively. This implies that, on average, the current level of output can be produced with 30% less inputs. Most farmers are applying either lower or higher volumes than the economically optimal dose. The average allocative efficiency of water is about 82%. We also found that water values were highly affected by the water-use efficiency of farms.

The simulation results of the effects of improving technical efficiency on marginal values of water applied for irrigation show that the value of the marginal product curves upwards, thereby raising water value. By operating at full water economic efficiency, the sampled farms would be able to reduce their costs of wheat production to 42%. Technical and allocative efficiencies account for 61% and 39% of the total water cost reductions respectively. This suggests that there is a wide scope to improve production efficiency and enhance the valuation of water resources used for the irrigation of wheat in Tunisia.

Finally, it should be noted that our analysis was based on information of farms in one single region. Additional research with panel data would be more scientific and reasonable.

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