Applied Mechanics and Materials Vols. 275-277 (2013) pp 2718-2722
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doi:10.4028/www.scientific.net/AMM.275-277.2718

A Worldwide Comparison of Water Use Efficiency of Crop Production

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Keywords: Cobb-Douglas production function; Stochastic frontier analysis; Variance decomposition; Water use efficiency of crop production

Abstract. Worldwide food security and water safety issues necessitate countries with low water use efficiency of crop production (CWUE) to increase it and reduce regional CWUE variations. CWUE function was estimated with stochastic frontier analysis, and CWUE variation was decomposed on inter-continental, intra-continental and international level with variance decomposition method. It is proposed that in order to efficiently improve the CWUE and reduce regional CWUE variation, countries with low CWUE should focus more on the factors listed from the decomposition. Scenario analysis proved the effect of improving the most important factor of CWUE variation, and showed some new key factors in the future after we realize the improvement as mentioned in the scenarios. Lastly we put forward some specific suggestions on the way to improve the CWUE.

Introduction

Food shortage and water safety have been becoming critical concerns related to sustainable crop production [1]. Accordingly, water use efficiency of crop production (CWUE) becomes one of the prime targets for any water conservation effort. The CWUE is always defined as the ratio of productivity to water used [2], or the ratio of yield to irrigation water requirement. Here it is discussed on the annual level and defined as (1), where *CWUE*, *Y* and *W* denote respectively annual water use efficiency of crop production, annual production of crops, and annual water investment of crop production.

$$CWUE=\frac{Y}{W}. \tag{1}$$

We've found that existing CWUE comparisons mainly involve water use in different conditions of the same region, or only focus on some specific items, or address usage efficiency of other resources combined with water use efficiency [3]. We haven't found any research that zooms in on the comparison of CWUE for crops worldwide, gives a more complete representation of CWUE disparities in the world, and provides recommendations for crop-production improvement in countries with lower CWUE, as well as the regional coordinated development. And we will try to address them.

Methods and Data

Methods. The CWUE variation model is built based on the Cobb–Douglas production function, and the SFA and variance decomposition are also adopted here.

Difference Model. The model would be formed as (2). The Y_{it} - crop production, A_{it} - total factor productivity, K_{it} - capital investment for crop production, mainly relevant to the land development [2], machinery & equipment and plantation crops in the agriculture, L_{it} - labor investment, W_{it} - water investment, and β_1 , β_2 , β_3 - productive elasticity of the factors above. All those indicators are relevant to the region i in the year *t*. Then both sides of the equation are divided by W_{ij}, and it shows (3)

$$Y_{it} = A_{it} K_{it}^{\beta_1} L_{it}^{\beta_2} W_{it}^{\beta_3} . \quad (2)$$

$$\frac{Y_{it}}{W_{it}} = A_{it} \left(\frac{K_{it}}{W_{it}}\right)^{\beta_1} \left(\frac{L_{it}}{W_{it}}\right)^{\beta_2} W_{it}^{((\sum_{j=1}^{3} \beta_j)-1)} . \quad (3)$$

The $\frac{Y_{it}}{W_{it}}$ is the CWUE, reflecting the output supported by a unit of water in the region; the $\frac{K_{it}}{W_{it}}$ and $\frac{L_{it}}{W_{it}}$ are the capital-water efficiency and labor-water efficiency, which reflect amounts of respective factors supported by a unit water. This formula implies that CWUE of a region is determined by total factor productivity, capital-water efficiency, labor-water efficiency, and water investment. Formula (4) shows the CWUE comparison in region *i* and *j*. The CWUE difference is the weighted product of four differences, with weights represented by a corresponding productive elasticity.

$$\frac{Y_{it}}{W_{it}} \Big/ \frac{Y_{jt}}{W_{jt}} = (A_{it}/A_{jt}) \left(\frac{K_{it}}{W_{it}} \Big/ \frac{K_{jt}}{W_{jt}} \right)^{\beta_1} \left(\frac{L_{it}}{W_{it}} \Big/ \frac{L_{jt}}{W_{jt}} \right)^{\beta_2} \left(W_{it}/W_{jt} \right)^{((\sum_{j=1}^{3} \beta_j)-1)} . \quad (4)$$

Then taking logarithm and variance decomposition [4], we can obtain the following notation (5):

$$Var\left(\ln \frac{Y_t}{W_t}\right) = Cov\left(\ln A_t, \ln \frac{Y_t}{W_t}\right) + Cov\left(\beta_1 \ln \frac{K_t}{W_t}, \ln \frac{Y_t}{W_t}\right) + Cov\left(\beta_2 \ln \frac{L_t}{W_t}, \ln \frac{Y_t}{W_t}\right) + Cov\left(\left(\left(\sum_{j=1}^{3} \beta_j\right) - 1\right) \ln W_t, \ln \frac{Y_t}{W_t}\right) . \quad (5)$$

Total Factor Productivity Model. The factors related to total factor productivity can be grouped into four types: natural factors, crop management, agronomy management, human capital and systems [5,6]. The frontier technology analysis divides total factor productivity into frontier technology and technical efficiency components [7]. Considering the similarity of the conditions in countries of the same continent, such as natural factors, economic policy(e.g. European Union), and the potential more frequent communication of technology and management, it would be assumed that the frontier technology varies by continent, but is more or less uniform in countries throughout the same continent. The total factor productivity function then should be re-written as (6):

$$A_{it} = \exp\left(A_0 + \sum_{i=1}^{5} (\tau_i t d_i) + V_{it} - U_{it}\right) . \quad (6)$$

The A_0 is the initial total factor productivity, and *t* is the time trend. The τ_i represents the frontier technological progress rate, and di indicates if the country belongs to a continent in question. It is equal to 1 if a country belongs to the continent, and 0 if it doesn't. *i*=1,2,3,4,5 respectively indicates the continents of Africa, the Americas, Asia, Europe and Oceania. $U_{it} = U_i \exp(-\eta(t-18))$, where U_i is the technical efficiency, a set of non-negative random variables assumed to account for technical inefficiency in production, having a half-normal distribution. η is the parameter to be estimated. We assume V_{it} *i.i.d.* $\sim N(0, \sigma_v^2)$ as being independent of the $U_{it,}$ to account for random variables' effect (e.g. weather). Combining the formulas (6) with (2) and taking the logarithm of the result, we arrive at relationship (7) - the stochastic frontier production function. Then we evaluate the stochastic frontier production function (7) in R using maximum likelihood estimation, replacing σ_v^2 and σ_u^2 with $\sigma^2 = \sigma_v^2 + \sigma_u^2$ and $\gamma = \sigma_u^2 / (\sigma_v^2 + \sigma_u^2)$ (where the σ_u^2 is the variance of U_i).

$$\ln Y_{it} = A_0 + \sum_{i=1}^{5} (\tau_i t d_i) + \beta_1 \ln K_{it} + \beta_2 \ln L_{it} + \beta_3 \ln W_{it} + V_{it} - U_{it} . \quad (7)$$

Data. This research utilizes relevant data in the years 1990-2007 for 87 countries. Data come from the FAO STAT or UN. We've chosen (8) to estimate the annual water investment of crop production.

$$W_{it} = (P_{it} - RW_{it}) * \frac{CA_{it}}{TA_{it}} + AWW_{it}\,. \quad (8)$$

The P_{it} is the average precipitation in volume; RW_{it} - total internal renewable water resources; CA_{it} - cultivated area; TA_{it} - total area; AWW_{it} - annual agriculture water withdrawal.

Results

Estimation Result. Production function has been estimated with the result summarized in the TABLE I. Comparing the τ_i value for five continents, we encounter wildly varying frontier technological progress rates. Oceania scores highest, it's frontier technological progress rate being 1.81 times as high as that in Africa and 1.47 times as high as that in the Americas. This disparity reflects total factor productivity differences between continents.

TABLE I RESULT OF PRODUCTION FUNCTION ESTIMATION

Parameters	A_0	β_1	β_2	β_3	τ_1	τ_2
Estimation	3.6522351*** (13.5353)	0.1545310*** (4.1032)	0.1807067*** (10.0091)	0.4645632*** (13.0345)	0.0232657*** (5.6181)	0.0287475*** (8.2416)
Parameters	τ_3	τ_4	τ_5	σ^2	γ	η
Estimation	0.0262455*** (7.3311)	0.0241949*** (8.0337)	0.0421519*** (4.4013)	3.1542154*** (7.2663)	0.9777525*** (292.9211)	-0.0057014*** (-3.8099)

Variation Analysis. Our results show CWUE varies greatly among continents. We analyze CWUE variation on inter-continental, intra-continental and international level. All the analysis includes two aspects, which is changes of both the CWUE variation and each contributing variation factor, and specific factor contributions and their respective variations. Those with relatively lower CWUE should focus on some key factors of the CWUE variation, including those greatly or increasingly fluctuating factors, or factors of which the contribution rate is large or increases or fluctuates a lot.

Inter-continental Disparities. As the disparity between the frontier technological progress rates in Africa and Oceania can be found to be the greatest, the variation of the CWUE in Africa and Oceania is decomposed in the current chapter, to assess the impact of each contributing factor. We can find changes of both the CWUE variation and each contributing variation factor are different from each other. And the main reason of the lower CWUE in Oceania is that the labor-water efficiency in Oceania is only 53.32% of that in Africa. Contribution changes of variation factors are also various.

Intra-continental Disparities. In Africa, the Americas and Asia, CWUE variation fluctuates insignificantly, while decreasing by a margin in Europe, and with increasing trend in Oceania. Trends of CWUE variation factors vary among different continents. In recent years, water management in Asia has been improved a lot, reflected in the decrease of the water investment difference (diff.) we observe. In Europe, decrease of total factor productivity diff. is also consistent with agronomy and crop management in this region. In Oceania, water investment diff. between countries is especially stark, and exerts primary influences on CWUE variation factors (except for the total factor productivity diff.). The main factors that contribute towards CWUE variation always vary among different continents. In Oceania it is water investment diff. among countries, while for other continents, for the most time, it is the total factor productivity diff.. Comparing the variation coefficient for the "Annual Agricultural Water Withdrawal" and "Water Investment for Crop Production", we find that "Annual Agriculture Water Withdrawal" fluctuates greater. Therefore, improvements in agricultural water withdrawal are very important for countries with lower CWUE in Oceania. Finally, comparing contribution rate trends for every CWUE variation factor, substantial differences between continents are noteworthy.

International Differences. The CWUE variation among countries in 1990 - 2007 can be decomposed (Fig.). On average, both CWUE variation and total factor productivity disparities between countries worldwide have decreased from 1990 until 1992, and have been relatively stable since. Other CWUE variation factors, like water investment diff., show no significant change, with the frontier technology diff. being close to 0 in any given continent. The key factor turns out to be the technical efficiency diff., contributing up to 80.06%. Overall, contribution rates for every CWUE variation factor show little change over the years.

Variation Analysis Conclusions. In the variation analysis above, we show the CWUE variation on inter-continental, intra-continental and international level. Key factors of the CWUE variation on each continent are summarized in the Table II.

Scenario Analysis. Based on the assumption that the most important factor of the CWUE variation is improved in the six kinds of comparisons in the respectively 5 continents and the international level, the scenario analysis can be developed. This would help further understand the impact of improving the most important factor. The scenarios from 1990 until 2007 are listed as follows, where the "level" indicates the level of water investment in Oceania, and that of total factor productivity in other regions.

S_0: no change of the original level;

S_1: all those countries with the level lower than the average, increase to the average level;

S_2: all those countries with the level lower than 80% of the average, increase to 80% of the average;

S_3: all those countries with the level lower than 60% of the average, increase to 60% of the average.

Then we calculate the new CWUE variation and decompose it.

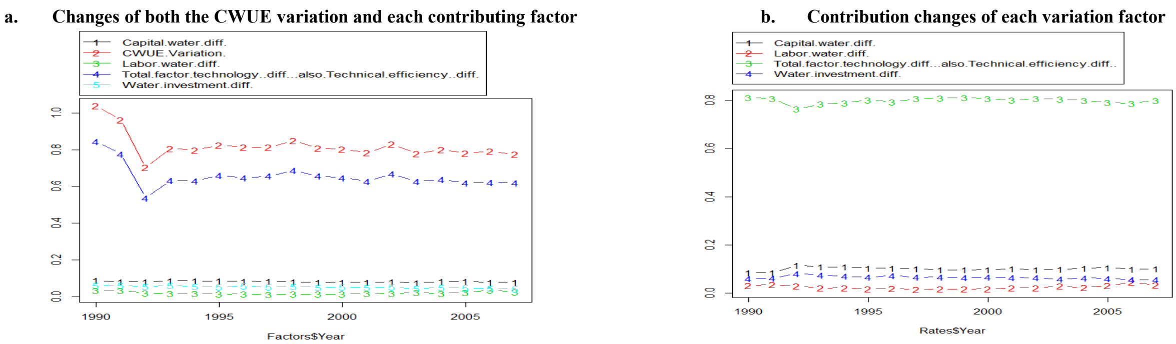

FIGURE RESULTS OF CWUE VARIATION DECOMPOSITION INTERNATIONALLY

TABLE II KEY FACTORS OF THE CWUE VARIATION ON EACH CONTINENT

Continent	The Most Important Factor	The Second Most Important Factor	Factors Fluctuating Greatly or Increasingly	Factors With Contribution Rate Fluctuating Greatly or Increasingly
Africa	Total factor productivity diff.	Capital-water diff.	/	Total factor productivity diff.
The Americas	Total factor productivity diff.	Capital-water diff.	/	Labor-water diff.
Asia	Total factor productivity diff.	Labor-water diff.	Labor-water diff.	Total factor productivity diff.; Capital-water diff.; Labor-water diff.
Europe	Total factor productivity diff.	Capital-water diff.	Total factor productivity diff.; Capital-water diff.; Labor-water diff.	Labor-water diff.
Oceania	Water investment diff.	Labor-water diff.	Total factor productivity diff.; Capital-water diff.; Labor-water diff.; Water investment diff.	Total factor productivity diff.; Capital-water diff.

It can be found that the CWUE variation under S_1, S_2, S_3 would become much smaller than that under S_0. This can prove that it is effective to improve the most important factor. So some countries like Zambia, Costa Rica, Bangladesh should make efforts to increase their total factor productivity.

Also we can conclude two features of the gap between the CWUE variation under either S_1, or S_2, or S_3, and that under S_0. Firstly, it varies among comparisons. In Asia or Oceania, CWUE variation under either S_1, or S_2, or S_3, is always less than 35% of that under S_0. While on any other level, the former is always more than 48% of the latter. Secondly, the trend of this gap varies in different comparisons. It is obviously increasing in Europe, while not significant in any other comparison. These two features are due to two aspects. One is the different contribution rates of the most important factor in different regions, and the other is that the distribution of water investment in Oceania and total factor productivity in other regions are always various among regions. So the effect of improving the most important factor would vary among different continents or on the international level.

We also propose that after improving the most important factor of the CWUE variation in the scenarios, countries with lower CWUE at that time should also pay more attention to the new key factors of the CWUE variation. From the results, these factors would be the capital-water efficiency diff. and water investment diff. in Africa, total factor productivity diff. and water investment diff. in the Americas, Asia, Europe or on the international level, and the total factor productivity diff. in Oceania.

Conclusions

This article has summarized and decomposed CWUE variations in 87 countries from 1990 until 2007. It is proposed that in order to efficiently improve the CWUE in the countries and decrease the regional CWUE variation, those countries with relatively lower CWUE should give priorities to water conservation and use efficiency improvement, focusing on the listed key factors. The scenarios analysis can prove the significance of improving the most important factor of the CWUE variation, and give us some new key factors in the future after we realize the improvement.

Additionally, total factor productivity diff. is the most important factor in the comparisons except that in the Oceania, where it is also one of the key factors. So here we give some recommendations for its improvement, including bio-water savings techniques [2], reduced soil evaporation, reasonable structure allocation of the knowledge-based and skilled human capital, and good systems.

Those countries with unscientific factor compositions in the crop production should make efforts to optimize the investment. Water investment can be improved by managing the water supply according to the demand, especially for those countries with low CWUE in the Americas and Oceania; countries in Africa and Europe should properly open the finance market, improve the investment and financing mechanism, and optimize the capital structure in the agricultural economy; it is also important for countries in Asia to scientifically manage the population, enhance the education in the rural areas as well as the reasonable flow of the labors, which can benefit the improvement of labor-water efficiency.

Methods used in this research can also be applied for analyzing most other resource efficiencies. Functions, indexes and data might be further expanded upon, with every factor checked for applicability. Factor analysis and variance analysis could be combined together to provide new insights and predict scenarios with a different number and composition of factors.

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