Determining water use efficiency for wheat and cotton: A meta-regression analysis

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Abstract

A great challenge for agricultural production is to produce more food with less water, which can be possibly achieved by increasing crop water use efficiency (WUE). We systematically reviewed 51 cases from 48 empirical studies with field experimental results on wheat and cotton. We estimated the yield-water use relations under both furrow and micro irrigation systems, compared crop water use to achieve maximum WUE and maximum yield, and evaluated the effects of many influential factors using meta-regression analysis. Our results showed significant effects of micro irrigation adoption, farm management practices focusing on crop, soil and water, and some moderator variables related with the empirical studies on crop WUE. Assessments of the publication selection bias and genuine effects illustrated the application of weighted least squares in conducting meta-regression analysis.

Key words**:** Water use efficiency, micro-irrigation, farm management practices, wheat, cotton, meta-analysis, publication bias

JEJ Codes**:** Q15, Q25, Q55

1. Introduction

With a rapid growth of the world population, limited fresh water resources are taking an increasing pressure from multiple users. Agriculture is the largest water-consuming sector and the shortage of water resources has become a big concern and affects the sustainable crop production. In many countries, due to the influence of different climatic conditions, rainfall is either scarce or highly variable. For example, the annul precipitation is less than 200 mm in arid areas of Hexi Corridor, Gansu Province, northwestern China (Huang et al., 2012); it's only about 105 mm in Xinjiang Province, China, and a majority occurs from June to August (Kang et al., 2012); in North China Plain (NCP), although the mean precipitation is 500-600 mm, the annual crop evapotranspiration (ET) 800-900 mm considerably exceeds the precipitation (Jin et al., 1999; Liu et al., 2002). Therefore, to offset water deficit and maintain a high crop grain yield (GY) in these areas, irrigation is heavily relied on in agricultural production. Due to the lack of surface water in many districts, especially northwestern China and NCP, Southern Texas High Plains of U.S., Uzbekistan, Syria, Turkey and India, groundwater becomes a primary source for agricultural irrigation, resulting in persistent declining of groundwater levels and considerably large zones of groundwater depression (Bordovsky et al., 1999; Du et al., 2006; Ibragimov et al., 2007; Liu et al., 2011; Oweis et al., 2011; Singh et al., 2010; Yazar, Sezen, and Gencel, 2002).

Limited availability of irrigation water requires some fundamental changes in irrigation management and promotes application of water saving techniques. Traditionally, furrow, flood and basin irrigations are among the common irrigation methods. By applying these methods, the cropland is generally over irrigated, resulting in heavy loss of water and low water use efficiency (WUE) (Yazar, Sezen, and Sesveren, 2002). Micro irrigation systems (e.g., drip emitters, drip tape, spray, and sprinklers), either spraying water to the plants or dropping water near the root zone, save 30-70% of the irrigation water and gain increasing popularity in irrigated agriculture (Ibragimov et al., 2007; Kang et al., 2012; Yazar, Sezen, and Sesveren, 2002). With unique agronomic and economic advantages, micro irrigations also show the potential of precisely applying water and chemicals across croplands which reduces labor and energy inputs (Gärdenäs et al., 2005). Much research regarding the irrigation effects on cotton demonstrated that micro irrigation systems led to improved yields and more efficient water use than the traditional methods (e.g., Bucks et al. (1988); Hodgson et al. (1990); Mateos et al. (1991)). Comparative studies between micro irrigation systems and traditional irrigation methods have revealed a significant increase of grain yields, harvest index and water use efficiency (Schneider and Howell (2001); Cetin and Bilgel (2002); Yazar, Sezen, and Gencel (2002); and Ibragimov et al. (2007)), provided that the irrigation systems are properly designed, managed, operated and maintained.

As a statistical tool earning an increasing attention, meta-regression analysis (MRA) is used to analyze data points obtained from separate empirical studies (Phillips, 1994; Stanley and Jarrell, 1989). MRA has the advantage of being able to systematically account for a complex set of potential factors that may influence some dependent variable in concern, and to draw conclusions from the analysis of literature (Loomis and White, 1996; Smith and Kaoru, 1990; Stanley, 2001). To the best of our knowledge, however, a comprehensive meta-analysis of the relation between WUE and irrigation systems as well as other farm management practices has not yet been conducted, and we aim to bridge this gap.

This paper studies and compares the WUE with estimation of production function under both furrow and micro irrigation systems and evaluates WUE of wheat and cotton using meta-analytical techniques. Specifically, the objectives of this study are: (1) to determine a plausible and comparable range of WUE for wheat and cotton based on a pooled database obtained from empirical studies, (2) to systematically explore the potential relationship between crop WUE and possible influential factors, especially the effects of micro irrigation and various farm management practices on crop, soil, water and fertilizer, and (3) to evaluate the application of MRA in synthesizing agricultural water management studies and examine the publication selection bias and other related issues.

2. Literature review

2.1. Crop water use efficiency and farm management practices

Higher WUE and/or higher yield can be achieved by applying various farm best management practices, for instance, no /minimum/rotational tillage, straw/film mulching, etc. The research by Hou et al. (2012) showed that comparing to conventional tillage the rotational tillage significantly improved soil moisture status, increased the amount of soil water stored during the wheat growing season and resulted in a 9.6%-10.7% increase of wheat yields and a 7.2%-7.7% increase of WUE. Cayci et al. (2009) studied the effect of rotation of winter wheat with five crops and fallow, and found the highest crop water use was determined in the preceding fallow treatment and the WUE values of winter wheat were higher in the preceding spring lentil treatment than in the preceding fallow treatment. Many other empirical studies investigated the crop WUE for varying water amounts applied and/or under different irrigation systems and the effects of climatic conditions, fertilizer levels, and mulching patterns (Albrizio et al., 2010; Chakraborty et al., 2008; Tolk et al., 1999; Xie et al., 2005; Zhao et al., 2012).

In addition, as water use efficiency can be effectively improved by reducing soil evaporation and/or increasing grain yield (Baumhardt and Jones, 2002; Howell et al., 2004), some other farm management strategies can be utilized in crop production. For instance, it is an effective way to reduce water use by leaving wheat under a slight drought stress in early growing stages and much research has been reported to show that a certain degree of soil water deficit can be kept during these stages at which crops are not sensitive to drought stress (Li et al., 2005; Schneider and Howell, 2001; Singh et al., 2010; Tang et al., 2010). Too much irrigation water resulted in low crop WUE and effective irrigation with less water could lead to a higher yield and WUE (Zhang and Oweis, 1999; Zhang et al., 2004). Thus, it is important and necessary to explore and interpret the relationship between WUE and GY, ET as well as the effects of crop, soil, water and fertilizer management practices and other relevant factors.

2.2. Meta-regression analysis

With the increasing application of MRA in the fields of health science, education and psychology, meta-analysis techniques have been introduced into economic studies (Stanley, 2001; Stanley and Jarrell, 1989) and explored by economists as a possible basis for assessing the nonuse value and nonmarket benefit transfer (Bateman and Jones, 2003; Bergstrom and Taylor, 2006; Johnston et al., 2003; Rosenberger and Stanley, 2006; Van Houtven et al., 2007), as well as for modeling the relationships of nonuse values and willingness to pay (WTP) for environmental goods and estimating the variability in WTP (Florax et al., 2005; Johnston et al., 2003; List and Gallet, 2001; Santos, 1998). For instance, Boyle et al. (1994) evaluated the willingness to pay for ground water contamination using meta-analysis. Loomis and White (1996) meta-analyzed the annual WTP for 18 different rare and endangered species, and demonstrated meaningful estimates of anthropocentric benefits of preserving these species by means of contingent valuation. MRA has also been applied to analyze farm productivity as affected by socio-economic factors (Phillips, 1994; Stanley et al., 2008).

In the fields of environmental and natural resource economics, agronomy and farm management, some studies conducting meta-analysis have been published. A summary of some recent meta-analysis studies is presented in the appendix A. There is some similar research on agricultural production and crop water use. For instance, Bravo-Ureta et al. (2007) meta-analyzed the farm level technical efficiency using 167 studies conducted around the world and found that varying estimates of the technical efficiency obtained were due to the differences of empirical models employed and variations at the country and continent levels. Both Pittelkow et al. (2015) and Zhao et al. (2016) analyzed the effects of no-till farming. Focusing on the farm productivity, Pittelkow et al. (2015) identified 678 studies representing 50 crops and 63 countries, and found that the best performance of no-till was for rainfed agriculture in dry climates given the evidence that the yields were equal to or higher than that of conventional tillage farming. With a comprehensive analysis of 39 studies in China, Zhao et al. (2016) pointed out that the adoption of non-tillage mitigated higher N2O emission in alkaline soils and under other conditions of fertilization and duration. Two fundamental meta-analysis studies were reported on crop water use. Sadras (2009) compared the effects of partial root-zone drying and conventional deficit irrigation on yields of multiple crops, and confirmed that the yield per unit water was higher by applying the partial root-zone drying and this method was also more feasible and economical. Qin et al. (2016) conducted a meta-analysis to evaluate the water and nitrogen use efficiencies in citrus production and found reductions of water use and fertilizer use might increase citrus yield, WUE and nitrogen use efficiency by 10-40%. Given the distinct objectives, however, the meta-analysis studies mentioned above (along with some others in the appendix A) employed varying analytical technique and/or econometric models.

Notwithstanding its growing application, meta-analysis has never been free from criticisms. A focal point of the critiques is that under-/over-estimation of the true effect may come from the publication selection biases[1] due to the higher probability of getting published for studies with significant results, unequal quality of study design and publications, aggregation of separate studies, unequal weights for the empirical studies included, selection and comparability of moderator variables, etc. (e.g., Phillips (1994), (Stanley, 2001, 2005), Stanley et al. (2008)). Publication bias reduces the validity and reliability of meta-regression analyses, that is, distorting the estimates of measures and making empirical effects seem larger than they actually are (Rosenberger and Stanley, 2006; Stanley et al., 2008).

To some extent, the quality of a meta-analysis is basically determined by how well the authors deal with and account for the publication bias. Some associated techniques to assess/correct the publication bias include funnel plot, funnel asymmetry test (FAT), and precision-effect test (PET). In addition, the weighted least squares (WLS) models with standard error or number of observations as weights are appropriate for meta-regression analysis (Stanley, 2005; Stanley et al., 2008; Stanley and Jarrell, 1989).

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[1]Given the great interest from social scientists and promising application of MRA, in 2005 a special issue in the Journal of Economic Surveys was designed to demonstrate the research scope that MRA can address and to showcase the tests that should be conducted along with MRA to cope with potential biases (see the articles by Roberts (2005), Stanley and Jarrell (1989), Stanley (2005), etc.)

3. Data and methods

3.1. Meta-data collection

To compare and evaluate WUE of wheat and cotton using different irrigation methods and farm management practices, it's critical to conduct systematic and exhaustive literature searches and screening[2]. In 2012, extensive literature searches were conducted within many academic literature databases and using several search engines, including Elsevier (ScienceDirect), Emerald, SpringerLink, Wiley, Google Search, Baidu Search and so forth. Some additional studies were located by scanning the reference lists of identified publications. We tried to identify as many empirical studies as possible, including both publications and gray literature.

A general procedure to choosing empirical studies for systematic reviews and meta-analysis was followed. Figure 1 shows the literature searching and screening process. Approximately 570 articles relating to any combinations of relevant keywords, e.g., water use, crop yield, water use efficiency, farm/crop/soil/water/fertilizer management, wheat, and cotton, etc. were reviewed initially. During the initial search, we learned the scope of studies on crop WUE as well as irrigation and farm management strategies, including the nature of irrigation & farm management, field experiments, measurements of WUE, etc. Subsequently, two rounds of article screening were carried out. The first screening excluded articles not related to irrigation, i.e., no irrigation applied, other crops, only reporting tillage or fertilizer

[2]As our database has not been updated since 2013, instead of comprehensively reviewing the WUE literature, this study focuses on investigating some general patterns of WUE studies in the literature in addition to the estimation of water use, yield and WUE relations.

application while no information on water use, etc. Through screening and reading the diverse empirical studies, we tried to understand the heterogeneity of WUE studies and interactions of multiple practices, including definitions, multiple farm best management practices, climatic conditions and their effects, etc. The second screening excluded articles from which we were unable to obtain or calculate WUE values, and included some most relevant articles from scanning the reference lists. After two rounds of article screening, 72 empirical studies focusing on WUE under different irrigation systems and using farm management strategies remained. They met some preliminary identification guidelines including articles should present crop WUE values or values of crop yield and volume of water use, as well as factors and information related to the publication and the study sites. Afterwards, during the final screening, the identification guidelines were supplemented with additional information, including clear identification of climate type of the study area, year the study conducted, number of observations, etc. In the end, 48 articles remained for the meta-analysis, specifically, 27 empirical studies for wheat and 21 for cotton.

Note although the literature searches were conducted in English and Chinese, the number of identified publications that provided complete and comparative information of wheat and cotton WUE for meta-analysis was limited. Unfortunately many studies just focused on either determination of crop water use and yield or application of irrigation water without reporting their effects on WUE. All the finally selected articles presented explicit values of WUE or values of crop yield and water use which facilitated the calculation of WUE. In addition, these articles provided direct or indirect information regarding all predictor and moderator (characteristics of publications) variables mentioned below. The

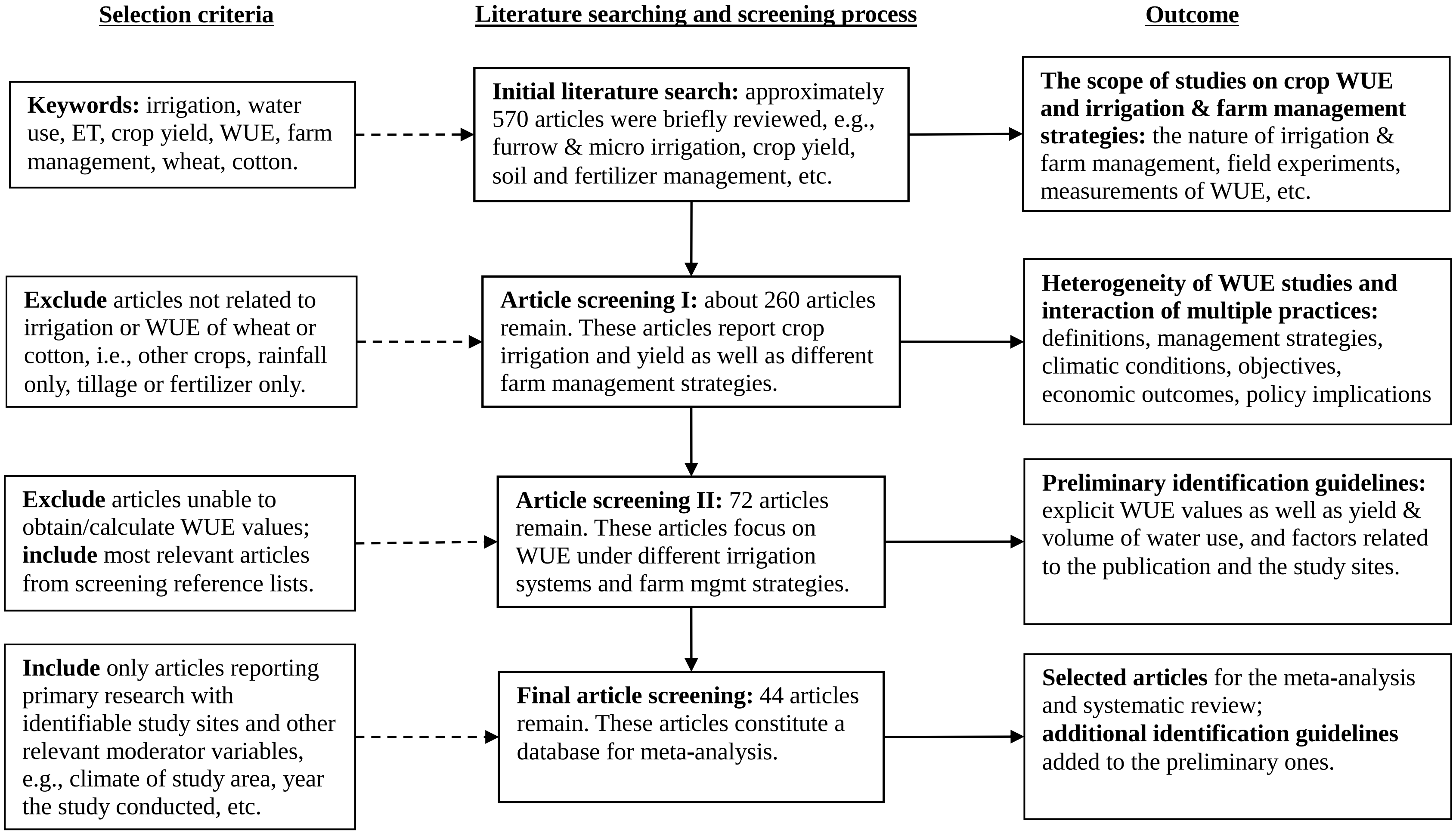

Figure 1. Flowchart of literature searching and screening process for selecting samples included in the meta-analysis.

identification process was repeated three times to ensure consistent data classification.

3.2. Defining water use efficiency

Water use efficiency can be calculated as units of dry grain yield per unit cropland (Y, $kg\ ha^{-1}$) divided by the units of water consumed by the crop (ET, mm) to produce that yield (Ibragimov et al., 2007).

$$\text{WUE} = \frac{Y}{ET} \tag{1}$$

where WUE refers to crop water use efficiency and the unit is $kg\ m^{-3}$, which can be unified with the unit $kg\ ha^{-1}\ mm^{-1}$ following:

$$WUE_{a,(kg\ m^{-3})} = WUE_{\ b,(kg\ ha^{-1}\ mm^{-1})}/10 \tag{2}$$

ET is crop evapotranspiration, and usually expressed as a depth of water (mm). ET consists of the water from precipitation (P), irrigation (I) and soil water content change (ΔW) while excluding the surface water runoff (R) (Tong et al., 2007):

$$ET = P + I + \Delta\text{W} - R \tag{3}$$

In this study, the mean values of WUE for wheat and cotton were calculated from each empirical study and used as a dependent variable in the meta-regressions.

3.3 Independent variables

In applying meta-regression analysis, moderator variables can be included as well as predictor variable that we are interested in. As proposed by Stanley et al. (2008), among others, the moderator variables can include: measures of estimate' precision, quality measures of original studies/empirical models, characteristics of the author and the data, etc. The predictor variables that we are interested in are: adoption of micro irrigation systems, farm management practices focusing on crop, soil, water and fertilizer, etc. All the independent variables and their descriptions and measurements are presented in table 1.

Measures of estimate' precision. Two measures are identified and used in this meta-analysis. *Se* is the standard error of WUE from each empirical study. *SQRT(n)* is a measure based on the number of observations reported. Both measures are continuous and can be used to account for publication bias and deal with heteroscedasticity (Liu and Richard Shumway, 2016; Stanley et al., 2008).

Characteristics of the data. *YEAR* represnts the year in which the experiment of the empirical study started (converted to an index by subtracting 1980). *NUM_YEAR* refers to the number of years that an empirical study (or an experiment) lasted. *NUM_DATA* is the number of data points obtained from an empirical study. These three measures reflect the characteristics of the data and they are continuous variables. All the rest independent variables are binary.

Adoption of micro irrigation systems. IRRI_MICRO is a dummy variable indicating the application of micro irrigation when conducting the field experiment (1 if applying micro irrigation and 0 if furrow irrigation).

Climate of the study area. CLIM_ARID indicates an arid or semiarid climate of the study area (1 if arid or semiarid and 0 otherwise).

Farm management practices. MGMT_CROP, *MGMT_SOIL*, *MGMT_WATER*, and *MGMT_FERT* indicate the empirical study investigated the effects of various management practices focusing on crop, soil, water and fertilizer (1 if yes and 0 if no).

Table 1. Meta-analysis variables and their measurements.

Variable	Description	Unit and measurement (wheat, cotton)	Mean (S.D.)	
			Wheat	Cotton
WUE	Mean of water use efficiency in a publication	Mean of WUE (ranges:0.54-1.73; 0.39-1.08)	1.13 (0.29)	0.65 (0.18)
Se	Standard error of WUE in a publication	SE of WUE (range:0.016-0.17; 0.002-0.145)	0.0583(0.04)	0.0376(0.04)
SQRT(n)	Square root of sample size in a publication	SQRT (n) (range:1.73-5.66; 1-7.48)	3.65(1.18)	2.85(1.42)
YEAR	Year in which a study was started, converted to an index by subtracting 1980	Year index (ranges:2-28; 14-29)	16.81 (6.31)	23.06 (3.64)
NUM_YEAR	Number of years a study lasted	Number of study years (ranges:1-13; 1-4)	3.59 (2.36)	2.33 (0.84)
NUM_DATA	Number of data points used to calculate the mean WUE, yield and ET	Number of data (ranges:3-32; 2-20)	14.67 (8.83)	9.56 (5.92)
IRRI_MICRO	Dummy variable indicating the micro irrigation was applied	Binary (range:0 or 1)	0.48 (0.51)	0.50 (0.51)
CLIM_ARID	Dummy variable indicating climate of the study area was arid or semiarid	Binary (range:0 or 1)	0.44 (0.51)	0.83 (0.38)
MGMT_CROP	Dummy variable indicating a study focused on crop management	Binary (range:0 or 1)	0.19 (0.40)	0.28 (0.46)
MGMT_SOIL	Dummy variable indicating a study focused on soil management	Binary (range:0 or 1)	0.41 (0.50)	0.06 (0.24)
MGMT_WATER	Dummy variable indicating a study focused on water management	Binary (range:0 or 1)	0.67 (0.48)	0.83 (0.38)
MGMT_FERT	Dummy variable indicating a study focused on fertilizer management	Binary (range:0 or 1)	0.19 (0.40)	0.17 (0.38)
IWUE	Dummy variable indicating irrigation water use efficiency (IWUE) was studied	Binary (range:0 or 1)	0.44 (0.51)	0.56 (0.51)
MULCH	Dummy variable indicating film or residue mulching was used in a study	Binary (range:0 or 1)	0.22 (0.42)	0.33 (0.49)
CHN	Dummy variable indicating a study was conducted in China	Binary (range:0 or 1)	0.56 (0.51)	0.33 (0.49)

Characteristics of the empirical study. *IWUE* indicates the study analyzed the crop irrigation water use efficiency (IWUE). *MULCH* means film or residue mulching was adopted in the experiment. *CHN* means the study area was in China. All the three measures are binary (1 if yes and 0 if no).

We hypothesize mixed effects from the moderator variables and positive effects from adoption of micro irrigation and other farm management strategies as these include general best management practices.

3.4. Econometric issues

To achieve efficient, consistent, unbiased and robust estimates, we need to examine multiple assumptions before estimating the regression models (Florax, 2002; Liu and Richard Shumway, 2016; Nelson and Kennedy, 2009). The studies included in the meta-analysis were distinct and independent. Correlations across observations should not be inferred. However, independence of the cases may be a problem for cotton as only one mean WUE value was used in all but three studies that reported WUE using both irrigation methods. In this case, failure to account for correlation in the same study may cause underestimation of standard errors (Liu and Richard Shumway, 2016). The Lagrange multiplier (LM) test can evaluate this issue and has been used in meta-analysis (Florax et al., 2005). Multicollinearity among independent variables can be a problem for a meta-analysis with relatively small number of studies and many dummy variables (Florax et al., 2005). A standard way to detect the existence of multicollinearity is to calculate the variance inflation factor (VIF) for each independent variable. A VIF less than 10 would indicate no multicollinearity problems. Heteroskedasticity can also be a problem for meta-analysis as the variances for the estimates of WUE in corresponding to each study would likely to be unequal. The White test or Breusch-Pagan test can be used to detect this problem. To deal with heteroskedasticity, a WLS approach is commonly employed in meta-regression analysis (Liu and Richard Shumway, 2016; Stanley et al., 2008). Two kinds of weights are the inverse of the standard error and the square root of sample size in each empirical study (Florax et al., 2005; Stanley et al., 2008; Stern, 2012). We will discuss the specification of WLS with the two weights in the model specification section below. In addition, the robustness can be checked by comparing estimates across various models, including ordinary least squares (OLS) and weighted least squares (WLS) models (Hubert and Rousseeuw, 1997; Tansey et al., 1996). The WLS is also reported to be robust in the presence of potentially omitted variables (Liu and Richard Shumway, 2016).

3.5. Econometric models for meta-regression analysis

We follow Stanley et al. (2008) to build the econometric models for the meta-analysis of crop WUE. A conventional regression model in applied economics research takes the form:

$$Y = X\beta + \varepsilon \tag{4}$$

where Y is the dependent variable (a $n \times 1$ vector, n is the number of observations), X is the independent variable (a $n \times k$ vector, k is the number of independent variables), and ε is the random error vector with mean zero and variance σ^2. β is the regression coefficients to be estimated (a $k \times 1$ vector).

In our case, the dependent variable is the mean of crop water use efficiency reported in each empirical study, and the independent variables include the predictor variables and moderator variables related with each article as proposed by Stanley and Jarrell (1989) and

Stanley et al. (2008). The OLS regression model can be specified as:

$$WUE = \beta + \sum_{k=1}^{K} \alpha_k Z_{jk} + e_j \quad (j = 1,\ 2,\ \dots\ J) \tag{5}$$

Where WUE is water use efficiency, and Z_{jk} is a vector containing all independent variables.

Alternatively, following Stanley et al. (2008) the equation (5) can be expressed in a generic form to ease the following derivation of the meta-regression models.

$$b_j = \beta + \sum_{k=1}^{K} \alpha_k Z_{jk} + e_j \quad (j = 1,\ 2,\ \dots\ J) \tag{5'}$$

where b_j represents WUE.

To correct the publication selection bias, according to Stanley et al. (2008), the MRA model can include the standard errors corresponding to the reported mean WUE.

$$b_j = \beta + \sum_{k=1}^{K} \alpha_k Z_{jk} + \beta_0 Se_j + e_j \quad (j = 1,\ 2,\ \dots\ J) \tag{6}$$

where β is the "true" effect when no publication selection and misspecification biases are present, and Se_j is the standard error of the sample mean WUE b_j in the j^{th} empirical study.

The MRA estimation procedure using OLS may suffer from heteroskedasticity problem (Stanley and Jarrell, 1989). Given the pooled nature of the meta-data, i.e., separate publications, distinct sample size, differing climate conditions for each study, etc. the OLS regression using the data may likely result in unequal variances. Thus the above equation (6) is also estimated using weighted least squares models. Either the inverse of standard errors or the square root of the number of observations can be used in WLS to obtain efficient estimates. The WLS model with the inverse of standard errors as weights can be expressed as:

$$b_j^{se} = \beta_0 + \frac{\beta}{Se_j} + \sum_{k=1}^{K} \alpha_k \frac{Z_{jk}}{Se_j} + u_j \quad (j = 1,\ 2,\ \ldots\ J) \tag{7}$$

where $b_j^{se} = \frac{b_j}{Se_j}$ is the weighted WUE estimate, and $u_j = \frac{e_j}{Se_j}$ is the error term with mean zero and variance σ_u^2. β_0 is the new intercept and its testing using t-test can indicate the effect of publication bias, i.e., FAT, and the slope coefficient β can be tested for authentic effect (correction for publication selection bias), i.e., PET (Stanley, 2005).

In MRA, if the standard errors are not provided or calculated in empirical studies, the inverse of the square root of sample size can also be used to account for publication selection bias, and accordingly thus they can be alternative weights to deal with heteroskedasticity. The econometric model specified in equation (6) and (7) can be expressed as:

$$b_j = \beta + \sum_{k=1}^{K} \alpha_k Z_{jk} + \beta_0 \frac{1}{\sqrt{n_j}} + e_j \quad (j = 1,\ 2,\ \ldots\ J) \tag{6'}$$

$$b_j^{n} = \beta_0 + \beta\sqrt{n_j} + \sum_{k=1}^{K} \sqrt{n_j}\alpha_k Z_{jk} + v_j \quad (j = 1,\ 2,\ \ldots\ J) \tag{7'}$$

where n_j is the number of observations in the j^{th} empirical study, $b_j^n = \sqrt{n_j}\, b_j$ is the weighted WUE estimate, and $v_j = \sqrt{n_j}\, e_j$ is the new error term with mean zero and variance σ_v^2. Using the dataset of crop WUE, we will illustrate the estimation of the two WLS models and compare with OLS. All the statistical analyses were conducted using the software SAS Version 9.4.

4. Results

4.1. Meta-data overview

An overview of the data set is presented in table 2. For wheat, 27 data sources across 9 countries with totally 396 observations were identified. For furrow irrigation, 14 publications with 205 observations were found, and for micro irrigation, 13 publications with 191 observations. Data on cotton were found from 21 sources across 5 countries with totally 172 observations. There were 10 publications using furrow irrigation and 14 cases using micro irrigation, with 82 and 90 observations, respectively.

Table 2. Summary of the database for meta-analysis.

		No. of cases	No. of publications	No. of countries	No. of observations
Wheat	Pooled	27	27	9	396
	Furrow	14			205
	Micro irrigation	13			191
Cotton	Pooled [a]	24	21	5	172
	Furrow	10			82
	Micro irrigation	14			90

a: three articles reported cotton WUE under both furrow and micro irrigations and thus each was considered as two cases in the meta-analysis.

The meta-data in this study comprise the 27 cases gathered from 27 unique studies on wheat and 24 observations from 21 studies on cotton. All of those studies were published from 1986 to 2012, and 42 out of the total 48 articles were published in 2000 or after. Appendix B summarizes some key characteristics of each publication. For cotton, the number of data sources exceeds the number of publications because three studies-Cetin and Bilgel (2002), Ibragimov et al. (2007) and Komilov et al. (2003) provided data under both furrow and micro irrigation systems. For other publications, varying observations were found under furrow or micro irrigation, thus the mean values for yield, ET and WUE were calculated from a single study and treated as individual cases. Note that the number of cases for wheat and cotton were different and less than the cases considered in some previous meta-analysis (Dalhuisen et al., 2003; Nelson and Kennedy, 2009; Rosenberger and Loomis, 2011; Woodward and Wui, 2001). There are three reasons: (i) as one of our goals was to determine crop WUE, diverse publications are identified and combined to reflect logical Yield-ET and WUE-ET relationships; (ii) all selected studies should be comparable and must have valid values for all the predictor and moderator variables to facilitate and analysis and integratiton; and (iii) reduction of stress on the data over expansion of data for meta-analysis should be favored (Bateman and Jones, 2003).

4.2. Yield-ET relations of wheat and cotton

Table 3 presents a statistic summary of yield, ET and WUE with data from empirical studies on a pooled basis. Since all the pooled data are analyzed, it is acceptable to see large ranges of yield variations for both wheat and cotton (CV=0.35 and 0.46, respectively). The ET range of 229.78-713.10 mm for wheat is broader than cotton’s, 332.56-780.50 mm. The ranges of WUE for wheat and cotton are 0.54-1.73 kg m^{-3} and 0.39-1.08 kg m^{-3}, with means 1.13 and 0.61 kg m^{-3}, respectively.

Table 3. Statistical description of yield ($\mathbf{kg\ ha^{-1}}$), ET ($\mathbf{mm}$) and WUE ($\mathbf{kg\ m^{-3}}$) for wheat and cotton. The minimum, maximum, mean, median, standard deviation (S.D.) and coefficient of variation (CV) of the data are calculated on a pooled basis of the primary empirical studies.

	Minimum	Maximum	Mean	Median	S.D.	CV
Wheat (n=27)						
Yield	1642.67	6965.13	4482.47	4459.11	1590.03	0.35
ET	229.78	713.10	399.01	374.07	122.33	0.31
WUE	0.54	1.73	1.13	1.15	0.29	0.26
Cotton (n=24)						
Yield	565.50	5750.00	2972.64	3026.80	1382.11	0.46
ET	332.56	780.50	486.42	465.87	117.69	0.24
WUE	0.14	1.08	0.61	0.61	0.24	0.40

It has been reported that the crop yield and ET relations can be presented by parabolic curves for both wheat (Kang et al., 2002; Sun et al., 2006; Wang et al., 2001; Zhang et al., 2006; Zhang and Oweis, 1999; Zhang et al., 2004) and cotton (Cetin and Bilgel, 2002;

Howell et al., 2004; Howell et al., 1984; Wanjura et al., 2002). Figure 2 depicts the yield-ET relations for wheat and cotton under furrow and micro irrigation systems. The optimal ET values for wheat are estimated to be 667 mm and 653 mm under furrow and micro irrigation to achieve the possible maximum grain yields of 6531 kg ha^{-1} and 6245 kg ha^{-1}, respectively. It indicates that the micro irrigation reduces water use by 2.1% and decreases grain yield by 4.4% compared with the performance of furrow irrigation. The optimal ET values for cotton are estimated to be 646 mm and 556 mm for furrow and micro irrigation to achieve the possible maximum seed cotton yields of 3823 kg ha^{-1} and 4806 kg ha^{-1}, respectively,

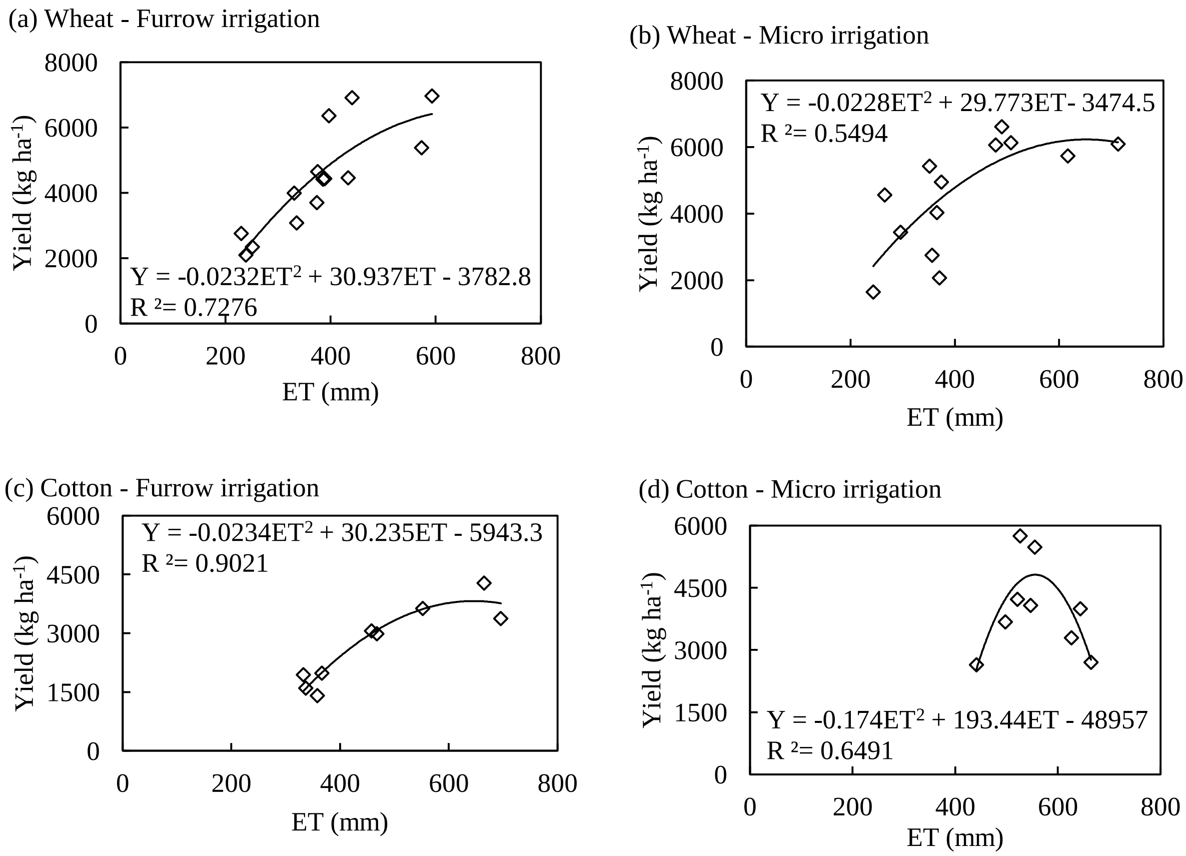

Figure 2. The yield (Y) and evapotranspiration (ET) relations for wheat and cotton under furrow and micro irrigation systems. For wheat, the grain yield is used to show the yield-ET relation and to calculate WUE, while for cotton, the yield of seed cotton is used.

implying that the water use reduces 14.0% and yield increases 25.7% by applying micro irrigation systems instead of furrow irrigation.

4.3. WUE of wheat and cotton

Figure 3 presents a histogram of wheat and cotton WUE values with clear patterns of their distributions. For the 21 cases of cotton, 7 studies have a mean WUE between 0.40 and 0.59 kg m^{-3}, 9 studies between 0.60 and 0.79 kg m^{-3} and 2 studies in each of the two upper and two lower categories. For the 27 cases of wheat, 7 studies present a mean WUE in the middle category, i.e., 1.00-1.19 kg m^{-3}. Two categories (1.40-1.59 and 1.20-1.39) on the right side have one more case than the two categories (0.40-0.59 and 0.80-0.99) on the left side. Nevertheless, the roughly symmetric histograms indicate the WUE values for wheat and cotton almost follow normal distributions.

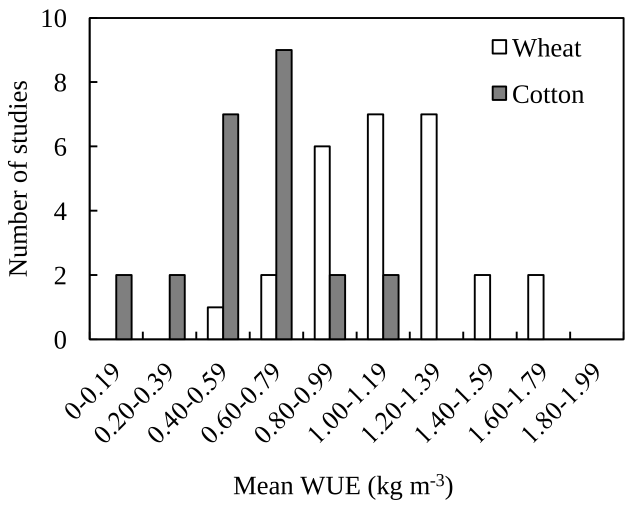

Figure 3. Histogram of mean WUE of wheat and cotton based on the pooled data.

A quadratic relationship between crop WUE and ET have been identified for wheat (Kang et al., 2002; Sezen and Yazar, 2006) and cotton (Howell et al., 2004) through conducting regression analysis using field experiment data. Figure 4 portrays the relationships between WUE and ET of wheat and cotton with the pooled data of furrow and micro irrigation systems. The optimal ET for wheat and cotton are 450 mm and 535 mm to realize the estimated maximum WUE of 1.04 kg m^{-3} and 0.88 kg m^{-3}, respectively. While through analyzing yield-ET relations of the pooled data, the optimal ET should be 646 mm to achieve the maximum yield of 6325 kg ha^{-1} for wheat, and 566 mm to achieve the maximum yield of 4162 kg ha^{-1} for cotton (not shown in figures). This finding implies that the maximum WUE can be realized by reducing crop water use by 30.4% and 5.5% for wheat and cotton, respectively, compared with the volume of irrigation water to achieve the

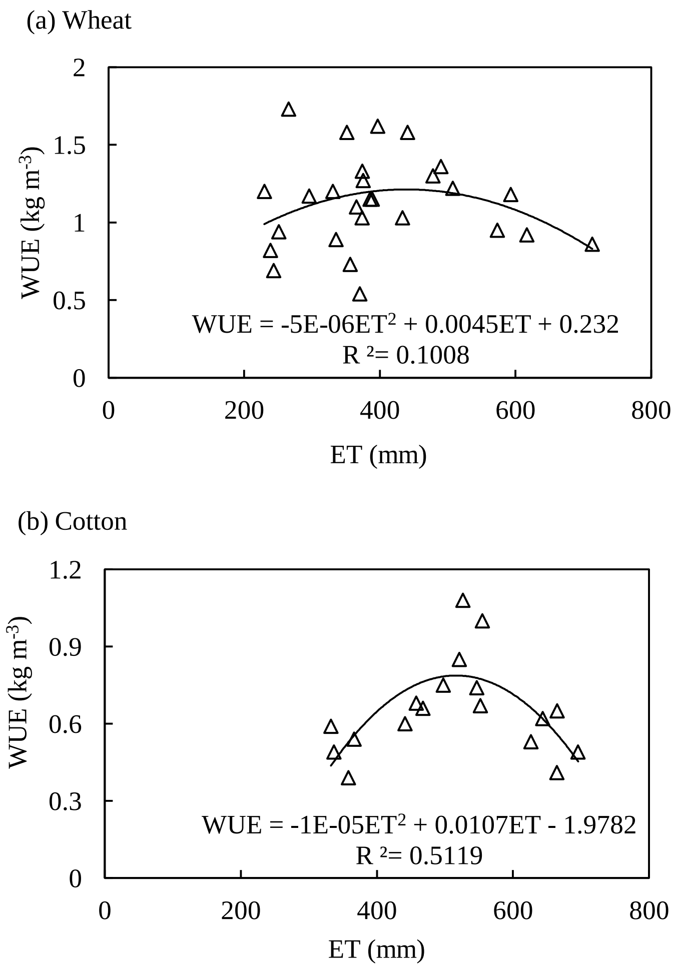

Figure 4. The WUE-ET relations of (a) wheat and (b) cotton with pooled data of both furrow and micro irrigations.

maximum yields. This confirms the recommendation many researchers have put forward: crop WUE could be significantly improved with reduction of irrigation water, for instance, using deficit irrigation (Jalota et al., 2006; Unlü et al., 2011; Zhang et al., 2004) and partial root-zone irrigation/drying (Du et al., 2006; Tang et al., 2010), etc.

4.4. Results of meta-regression analysis

To visually check for the publication selection bias, the funnel plots are presented in figure 5, which graph the WUE values with the precision of their estimates, $1/Se_j$. The scatterplot of WUE values should form a inverted funnel if no publication selection bias is present (Stanley, 2005). However, the two funnel graphs look fairly like funnels, which may indicate a publication selection biase or not. (Alternative funnel plots using square roots of sample size can not really conclude with the possible existence of pubilicaiton bias either, see appendix C.) In addition, the funnel asymmetry test can be conducted (table 4 and table 5). The t-tests of the intercepts in the two WLS models indicate we reject the null hypothsis of the absence of publication bias ($p<0.05$ for wheat; $p<0.01$ and $p<0.05$ for cotton). To test for genuine effect beyond the publication bias, t-tests of the slopes ($1/Se_j$ and $\sqrt{n_j}$) in WLS models can be used. Significant precision-effect tests show clear evidence of a positive WUE after the publication selection is corrected ($p<0.05$ and $p<0.01$for wheat; $p<0.05$ and $p<0.10$ for cotton). The positive coefficients suggest studies with higher WUE are more likely to be published or accpeted for publication by editors.

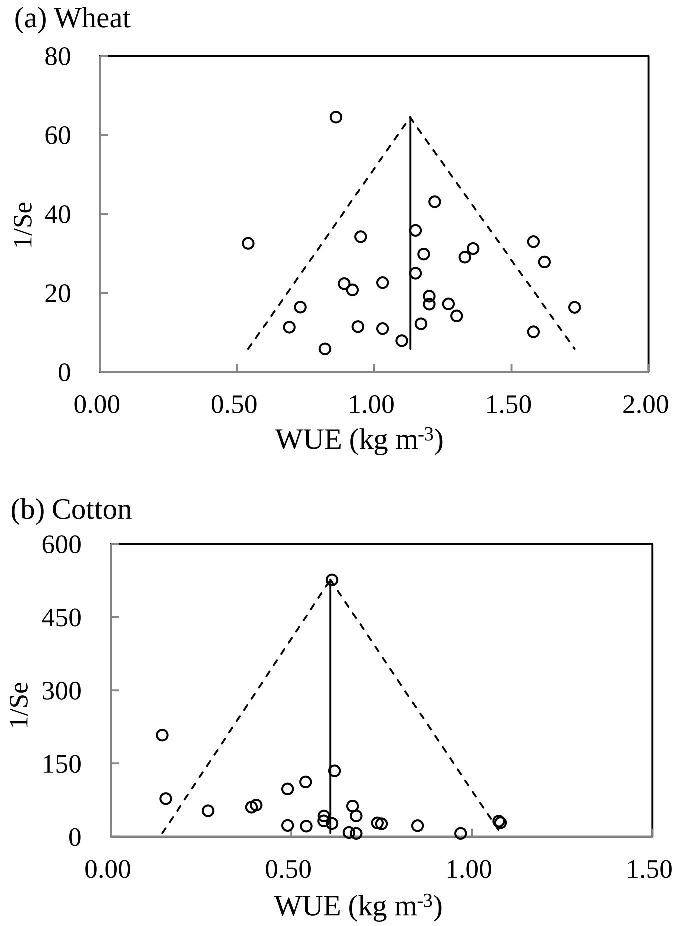

Figure 5. Funnel plots of WUE for (a) wheat and (b) cotton.

The empirical estimates of the meta-regression equations for crop water use efficiency using OLS and WLS are reported in table 4 for wheat and table 5 for cotton. The adjusted R^2 values are 0.335, 0.420 and 0.458 from the OLS and two WLS models for wheat, and 0.413, 0.534 and 0.492 for cotton, which are smaller than but close to the adjusted R^2 values in previous meta-regeression analysis by Liu and Richard Shumway (2016), Nelson and Kennedy (2009) and Stanley et al. (2008). The mean VIF values range from 2.31 to 7.82, indicating no concerns with multicollinearity.

Overall, more independent variables are significant in predicting cotton WUE than in predicting wheat WUE. The following interpretation will focus on the two WLS models as moderate heteroskedasticity exists in both wheat and cotton OLS models ($0.05<p<0.10$). Regarding the characteristics of data, the number of study years is statistically significant only for cotton, while the number of data is statistically significant for both wheat (only in WLS models) and cotton. This indicates more data presented in a empirical study are likely to be associated with higher WUE, probably because more data signal to editors that more work has been done and thus the article is more likely to be accepted. One effect of publication bias is to tempt authors to search for larger estimates as large-sample studies tend to have small standard errors (Stanley et al., 2008). The variable-the year starting the experiment is not significant.

Coefficient of the dummy variable micro-irrigation is positive and statistically significant in all the models for both wheat and cotton but at differing significant levels. In line with our expectation, this indicates that the adoption of micro irrigation can increase WUE through reducing both the volume of irrigation water and the water for evaporation (Ibragimov et al., 2007; Wanjura et al., 2002). The dummy variable on arid and semiarid climate is significant in predicting WUE for wheat (only in WLS models) and cotton. Crops in arid or semiarid climate require more water as a larger proportion of the water can evaporate, however, if scheduled well and complemented with appropriate best management practices, water can be saved in arid areas compared with the crop water consumption in humid climates.

The dummy variable regarding the adoption of crop management practices is significant only for cotton. Such practices like crop rotations, annual double cropping, planting catch crops and better crop varieties either reduce irrigation water use or improve the yield, thus

Table 4. Meta-regression analysis for water use efficiency (WUE) of wheat using ordinary least squares (OLS) and weighted least squares (WLS) models.

	OLS		WLS			
			(I) Weights: Se		(II) Weights: 1/SQRT(n)	
Explanatory variables	Coef.	Std. err.	Coef.	Std. err.	Coef.	Std. err.
Intercept	1.219**	0.497	3.899**	1.784	2.270**	1.081
Publication bias correction						
Se	1.286*	0.680				
1/Se			0.206**	0.091		
SQRT(n)					1.244***	0.341
YEAR	0.012	0.017				
NUM_YEAR	-0.016	0.043	-0.054	0.040	-0.036	0.040
NUM_DATA	-0.021	0.029	0.034*	0.019	0.058**	0.021
IRRI_MICRO	0.080***	0.027	0.157***	0.036	0.489**	0.228
CLIM_ARID	0.029	0.186	0.077**	0.031	0.086*	0.046
MGMT_CROP	0.034	0.213	0.156	0.195	-0.085	0.213
MGMT_SOIL	0.021	0.254	0.032	0.019	0.047*	0.025
MGMT_WATER	0.127***	0.040	0.051**	0.024	0.076**	0.032
MGMT_FERT	-0.161	0.559	-0.038	0.024	0.017	0.023
IWUE	0.037	0.188				
MULCH	0.043	0.289	0.040*	0.023	0.045*	0.024
CHN	0.028	0.018				
R^2	0.356		0.482		0.470	
Adj R^2	0.335		0.420		0.458	
N	27		27		27	
F	12.80		18.35		16.4	
Mean VIF	4.10		7.82		6.90	

*** Statistically significant at 1% level.
** Statistically significant at 5% level.
* Statistically significant at 10% level.

resulting in higher WUE (Ingram et al., 2012). The dummy variable on soil management practices is only marginally significant in WLS model (II) ($p<0.10$), however the negative and significant effect in cotton models is out of expectation, but very interesting. As the soil management practices generally refer to alternative/ rotational tillage, terracing maintenance, sowing, etc. (Ingram et al., 2012; Jalota et al., 2008), more empirical work is needed to investigate whether the negative effect indicates less activities in the cropland, for example,

Table 5. Meta-regression analysis for water use efficiency (WUE) of cotton using ordinary least squares (OLS) and weighted least squares (WLS) models.

	OLS		WLS			
			(I) Weights: Se		(II) Weights: 1/SQRT(n)	
Explanatory variables	Coef.	Std. err.	Coef.	Std. err.	Coef.	Std. err.
Intercept	0.591**	0.232	1.951***	0.664	2.470**	1.092
Publication bias correction						
Se	0.504***	0.165				
1/Se			0.292**	0.135		
SQRT(n)					1.405*	0.769
YEAR	-0.008	0.018				
NUM_YEAR	0.035***	0.005	0.023*	0.012	0.111**	0.046
NUM_DATA	0.063**	0.032	0.008***	0.002	0.035***	0.012
IRRI_MICRO	0.050*	0.029	0.052*	0.027	0.151*	0.087
CLIM_ARID	0.063*	0.035	0.034**	0.016	0.074**	0.033
MGMT_CROP	0.023**	0.009	0.111***	0.028	0.095**	0.035
MGMT_SOIL	-0.073**	0.028	-0.139**	0.063	-0.668**	0.267
MGMT_WATER	0.042*	0.022	0.080	0.072	0.196*	0.101
MGMT_FERT	-0.031	0.035	-0.986	0.983	-0.939	0.612
IWUE	0.036**	0.017	0.074**	0.028	0.835**	0.345
MULCH	0.016	0.013	0.073*	0.038	0.212**	0.098
CHN	-0.063	0.050				
R^2	0.446		0.558		0.566	
Adj R^2	0.413		0.534		0.492	
N	24		24		24	
F	14.1		20.35		21.44	
Mean VIF	2.31		5.69		7.65	

*** Statistically significant at 1% level.
** Statistically significant at 5% level.
* Statistically significant at 10% level.

no/minimum tillage, fallow fields. The dummy variable regarding the application of water management practices is significant for wheat and cotton (not significant in WLS model (I)). Consistent with findings from many empirical studies, conservation-oriented water practices can contribute to higher WUE by determining when and how much water is needed, for instance, investigation of crop water requirements and crop evapotranspiration during various growing stages, scientific irrigation scheduling, amount of effective rainfall, supplementary irrigation (Cayci et al., 2009; Kang et al., 2012). However the fertilizer management practices are not significant in predicting WUE.

The dummy variable indicating the investigation of IWUE is significant only in cotton models. Different from WUE, IWUE measures the crop water use efficiency while excluding the allowance of rainfall in the growing season. As IWUE is always greater than WUE for the same crop growing in the same season (Jiang et al., 2012; Sezen and Yazar, 2006), authors investigating both measures in one study are tempted to matching WUE with IWUE, resulting in higher WUE values which are favored in publication. The dummy variable of mulching is significant in both wheat and cotton WLS models. The adoption of mulching and residue management can lead to higher WUE (Chakraborty et al., 2008; Xie et al., 2005). Both film and straw mulching curtails evaporation from the soil and holds water near the root zone. In addition, residue management practices keeping straws in field improves the carbon sequestration in the long term, which benefits plants absorbing moisture from soil (Luo et al., 2010) .

Robustness checks can be conducted through comparing the changes of signs and significance level of the coefficients. For wheat models, the signs of coefficients mostly remain consistent, while three variables, i.e., NUM_DATA, CLIM_ARID and MULCH, become significant in both WLS models, and MGMT_SOIL becomes significant only in WLS model (II). This indicates the advantage of WLS to provide better model specifications in conducting meta-analysis. The outcomes from cotton models show much more robust estimates with consistent signs and significant levels.

5. Concluding remarks

In this research, we offer a meta-regression analysis of crop WUE focusing on 51 cases from 48 empirical studies published in 1986-2012. Through extracting data in empirical publications, we obtain a detailed database for wheat and cotton including their water use, yield, WUE, irrigation systems employed, farm management practices, as well as other moderator variables related with the publications. With this unique dataset, we try to determine a meaningful, comparable range of wheat and cotton WUE, explore the yield-ET relations, and evaluate the effects of micro irrigation and other farm best management practices on WUE. In the course of this exercise, we uncover several interesting findings.

1). Crop water use is different under different irrigation systems and also different for different crops. Comparisons based on the pooled database suggest micro irrigation could decrease crop water use by 2.1% and decrease the grain yield by 4.4% for wheat. While for cotton, a 14.0% reduction in water use can increase the yield by 25.7% if shifting from furrow to micro irrigation.

2). A relatively broad range of WUE is found for both wheat and cotton, i.e., 0.54-1.73 kg m^{-3} and 0.39-1.08 kg m^{-3}, respectively, and the mean values are 1.13 and 0.61 kg m^{-3}.

3). Based on the estimated quadratic relationships between WUE and ET, 30.4% and 5.5% of the water use can be saved for wheat and cotton if the goal of agricultural production is to achieve maximum WUE rather than the maximum yields.

The differing estimates of water use, yield and WUE are probably because the empirical studies were conducted under diverse climate conditions, irrigation systems, farm management practices, etc. Variations of these factors need to be considered jointly to evaluate crop WUE integrated from empirical studies.

To reveal systematic causal patterns for the investigated measures obtained in previous publications, many researchers in applied economics utilized meta-analytical techniques (Liu and Richard Shumway, 2016; Rosenberger and Loomis, 2011; Woodward and Wui, 2001). In our case, the meta-regression analysis is conducted using OLS and two WLS models to explore some fundamental effects through evaluating these predictor and moderator variables on a pooled basis. The illustration of MRA models on wheat and cotton WUE indicates distinct and fundamental effects of irrigation type, management strategies, and attributes of publication, which is consistent with the findings from meta-analysis (Johnston et al., 2003). The significant effects from multiple independent variables constitute the general patterns that we expected. For wheat, higher WUE is associated with growing in arid or semiarid environments, under micro irrigation systems, water management practices and cropland mulching. Meanwhile, more practices are effective to increase cotton WUE, including more crop management practices and less soil management practices in addition to those effective for wheat. Some data and publication characteristics like more years conducting the experiment and more numbers of data presented in a study are also associated with higher WUE. The WLS with appropriate weights not only provides efficient and robust estimates (Liu and Richard Shumway, 2016), but facilitates the testing of publication bias and genuine effects in a meta-regression analysis (Stanley, 2005; Stanley et al., 2008).

Though we notice some research reported a potential interaction effect of two or more jointly adopted farm management practices, unfortunately we cannot test this in the meta-analysis due to the limitation of our selected empirical studies. An update of the database can be made later, and more comparable predictor and moderator variables can be chosen to investigate other interesting patterns of farm best management practices and crop WUE.

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Appendix A

A summary of some recent meta-analysis studies on environmental & natural resources economics, agronomy and farm management.

Appendix B

A list of the selected empirical studies included in the meta-regression analysis.

Appendix C

Alternative funnel plots using the square root of sample observations.

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