Environ Dev Sustain (2017) 19:1247–1263
DOI 10.1007/s10668-016-9793-8

Improvement in irrigation water use efficiency: a strategy for climate change adaptation and sustainable development of Vietnamese tea production

Nguyen Bich Hong[1,2] · **Mitsuyasu Yabe**[1]

Received: 17 November 2015 / Accepted: 7 April 2016 / Published online: 12 April 2016

Abstract Irrigation is indispensable to overcome insufficient rainfall and to achieve a stabilized yield for tea production. As the severe scarcity of water resources because of climate change, water conservation through efficient irrigation has turned into a vital strategy for tea sector in solving this rising challenge. This paper analyzes irrigation water use efficiency of small-scale tea farms in Vietnam and identifies its determinants applying stochastic frontier analysis. Results showed that under decreasing returns to scale, the mean irrigation water use efficiency was 42.19 %, indicating the existence of substantial water waste. If farmers become more efficient in using water, saving 57.81 % of irrigation water is possible unaccompanied by reducing the observed output. The factors affecting tea farms' irrigation water use efficiency were investigated by Tobit model. Gender, water shortage awareness, soil and water conservation practice, off-farm income share, extension services access and well water utilization showed significant influence on the efficiency of irrigation water. The study' results provide insights to policymakers in implementing better water resource management amid climate change.

Keywords Irrigation water use efficiency · Tea production · Climate change · Vietnam · Stochastic frontier analysis

1 Introduction

Tea is the global second most prevalent drink (Szenthe 2015). Tea consumption in the world increased by 60 % in the period of 1993–2010, and considerable growth is predicted with more people becoming tea consumers (Brouder et al. 2014). Today, tea production

✉ Nguyen Bich Hong
nguyen.bich.hong85@gmail.com

1 Environmental Economics Laboratory, Department of Agriculture and Resource Economics, Graduate School of Bioresource and Bioenvironmental Sciences, Kyushu University, 6-10-1, Hakozaki, Higashi-ku, Fukuoka City, Japan

2 Thai Nguyen University of Economics & Business and Administration, Thai Nguyen, Vietnam

contributes to socioeconomic development in many poor countries. The tea 2030 steering group stated that tea is going to become a 'hero' crop for 2030 which brings significant benefits to not only millions of stakeholders in the sector but also the world (Brouder et al. 2014).

Tea is leading among Vietnam's cash crops and considered an important national sector with regard to job creation, foreign exchange earnings and poverty alleviation. The industry provides employment for about 400,000 small rural households (GSO 2011). Vietnam is the sixth largest global tea producer, yielding 185,000 tons in 2013 (Chang 2015). Export turnover from 132,000 tons sold oversea in 2014 grossed 228.12 million (GSO 2014).

However, the global tea production is confronting with unprecedented challenges, particularly from climate change and water scarcity, which threatens the future of this favored drink. Increasing temperatures and changing rainfall patterns, which cause drought and water scarcity, have already affected the quantity and quality of tea production, further threatening the livelihood security of susceptible tea smallholders in many major tea-producing countries such as China (Ahmed et al. 2014), India (Dutta 2014), Kenya (Kabubo-Mariara and Karanja 2007), Sri Lanka (Wijeratne et al. 2007) and Vietnam (Krechowicz et al. 2010).

In many climate change-affected regions where dry season becomes longer, tea growers have to depend on irrigation instead of rainfed amid the global severe water scarcity. Irrigated tea-based cropping systems are among the major water users in Vietnam. The total irrigated tea area was 62,551 hectares in 2005 (FAO 2015). Irrigation plays an important role in Vietnamese tea production, especially during dry season starting from November to May (Vietnamese Tea Association 2009). Water scarcity in Vietnam has worsened due to climate change, aside from challenges brought by agriculture production and rapid industrialization and urbanization (Giang et al. 2012). Water demand for Vietnamese agriculture by 2100 is predicted to increase double or triple times compared with 2000, which lead to the severe drought and water shortage for irrigation. The changing climate is also predicted to affect the northern part of Vietnam seriously (FAO 2011). The increasing scarcity of water and competing claims on water by other sectors impose more efficient water consumption for agriculture, particularly tea production.

This paper aims to estimate tea production's irrigation water use efficiency (IE) and detect its determinants based on data of 243 randomly tea farms in Vietnam. This study is significant amid the increased stress on water resources and limited supplies of irrigation water in tea production. It not only raises awareness on water use inefficiencies in tea sector but also suggests ameliorations for this problem through analyzing the factors affecting these inefficiencies. The paper also makes some contribution to the literature. Firstly, to our best knowledge, the researches on evaluating the efficiency of irrigation water use in tea production using stochastic frontier analysis (SFA) have not done in the world and in Vietnam in particular. SFA is an econometric method based on production frontier model in economic theory which expresses the ability of producers to maximize output with existing inputs or to produce the observed output with minimum inputs used. Secondly, in an attempt to obtain insight into the contributing factor of irrigation water use efficiency of tea production, not only farm-specific characteristics and socioeconomic features are considered, but also tea farmers' awareness of water shortage. There are a few empirical studies on tea production efficiency that examines simultaneously socioeconomic factors and psychological explanatory variable like perception. Moreover, if perception of water scarcity has impact on irrigation water use efficiency, a suitable program targeting tea farmers' behavior change may improve it.

This paper includes six sections. After introduction, Sect. 2 presents the methodological framework for measuring irrigation water efficiency. Section 3 explains the empirical model and data collection process. The results are introduced in Sect. 4. Meanwhile, discussion and policy recommendations were reported in Sect. 5. The final section includes conclusions drawn from the study.

2 Methodology

2.1 Irrigation water use efficiency estimation from economic perspective

Increasing *water use efficiency* is considered as a crucial mitigation in water resource management under the context of global water scarcity, climate change and food demand rising (Allan 1999; Gleick 1993; Pereira et al. 2009; Rockström and Barron 2007). Literatures on measurements of water use efficiency are found in Barker et al. (2003), Billi et al. (2007), Molden et al. (2010), Pereira et al. (2012), Scheierling et al. (2014), Schoengold and Zilberman (2007), Seckler et al. (2003), Sharma et al. (2015), Van Halsema and Vincent (2012) and Viaggi et al. (2014). These studies summarized that there have two major methods used to measure water use efficiency including hydrological or engineering approach and the economic approach.

In hydrological science, IE is the proportion of crop yield to observed water consumption, i.e., yield per m^3 (Billi et al. 2007; Sharma et al. 2015; Wang 2010; Zhang et al. 2004). However, this physical measurement overlooked that output is influenced by multiple inputs (fertilizers, pesticide, seeds, machine, labor, water) and not only by a single input (water) (Scheierling et al. 2014; Wichelns 2014). Speelman et al. (2008) indicated that such measure considers agricultural production as a process using only water to produce output and explains very little the differences among farmers. In addition, Coelli et al. (2002) argued that irrigation water efficiency, as defined above, is little applied when the utilization of non-water inputs among farms are different, and it does not fully reflect the efficiency of resource utilization in agricultural production as compared with the economic approach named technical efficiency (TE) which Farrell (1957) proposed. TE denotes the farmer's ability to maximize output from present inputs (output orientation) or to minimize inputs used to yield observed output (input orientation). Hence, it is essential to measure irrigation water use efficiency using economic method.

According to economic opinion, IE is a single-factor input-oriented TE which is the proportion of the minimum possible amount of water to the actual volume of water used, given observed output, and remaining inputs (Karagiannis et al. 2003). The concept of single-factor input-oriented TE was devised by Kopp (1981) and Atkinson and Cornwell (1994). Specifically, IE is given as:

$$\mathrm{IE} = [\min\{\lambda : f(X, \lambda W; \alpha) \geq Y\}] \rightarrow (0, 1) \quad (1)$$

where λ is the irrigation water use efficiency. W is the actual volume of irrigation water used. λW is minimum possible amount of irrigation water. X represents other inputs (fertilizer, pesticide, labor, capital, other costs, etc.). Y is the actual output. α represents unknown parameters.

This definition focuses on economic aspect of the irrigation water use instead of engineering aspect (Karagiannis et al. 2003). It provides information on amount of water

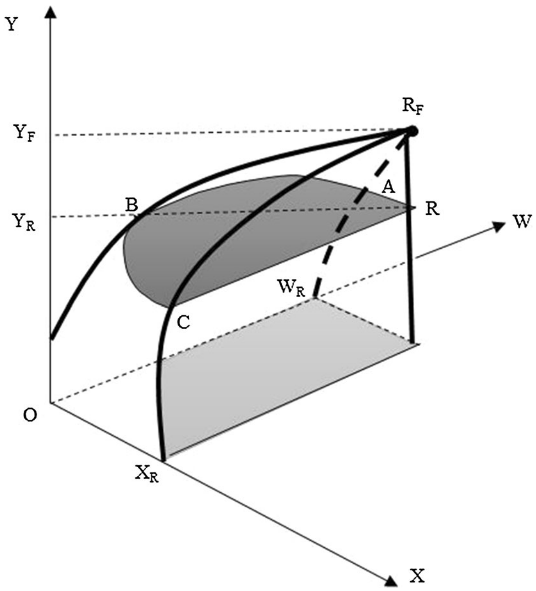

Fig. 1 3-D graphical illustration of technical efficiency measures. *Note* It is based on Reinhard et al. (1999)

reduced without changing volume of output and other inputs used. Figures 1 and 2 show the measure of technical and irrigation water use efficiency.

Figure 1 illustrates the production of output (Y) by using irrigation water use (W) and other used inputs (X), such as fertilizer, pesticide, labor, capital. The surface $OX_RR_FW_R$ describes the production frontier.[1] The point R_F presents the best production performance with maximum possible output (Y_F) produced by using irrigation water (W_R) and other inputs (X_F), while the point R depicts observed farm R producing the actual output (Y_R). The surface $ABCR$ represents the output quantity identity, Y_R, as farm R. The observed farm R is technical inefficiency, since it does not produce the maximum output level as R_F and overuses inputs compared with B or C which produces identical output level. The technical inefficiency can be improved by: increasing output level from R to R_F (output-oriented orientation) or reducing the level of all inputs used from R to B (radial input-oriented orientation) or contracting the level of a single input given other inputs from R to C (non-radial input-oriented orientation). In Fig. 2, a radial input-oriented TE, which considers the reduction in all inputs, is measured by $|OB|/|OR|$. Since irrigation water use efficiency is a non-radial input-oriented TE, which considers the contraction of single input as water, conditional on other inputs and observed output, it is measured by $|X_RC|/|X_RR| = |OW_F|/|OW_R|$. Färe (1978) indicated that non-radial efficiency measure is less than or equal to radial one.

In economic literature, two methods are widely used to estimate IE. First is the econometric approach named SFA which is devised by Aigner et al. (1977). Reviews of using SFA to estimate irrigation efficiency water use include Dhehibi et al. (2007), Karagiannis et al. (2003), McGuckin et al. (1992), Tang et al. (2014) and Watto and Mugera (2015). For instance, Karagiannis et al. (2003) proposed SFA to estimate irrigation water efficiency of 50 vegetable farms in Crete, Greece. The study showed that IE, on

[1] Production frontier shows maximum output possibilities that can be produced with current inputs used (Gans et al. 2011).

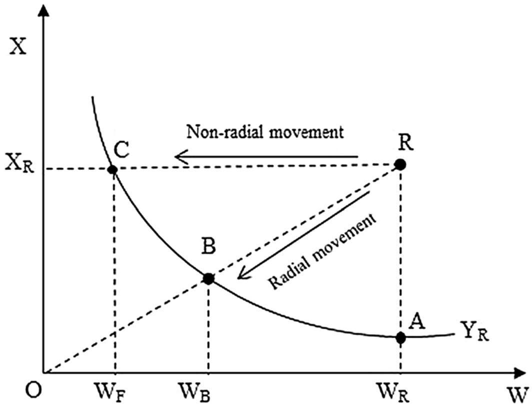

Fig. 2 Cross-sectional graph of input-oriented technical and irrigation water use efficiency measures. *Note* It is based on Karagiannis et al. (2003)

average, is 47.20 %, suggesting that 52.8 % saving of water use could be achieved without affecting current quantity of vegetables and given other inputs. In addition, the most significant factors having influence on irrigation water efficiency of vegetable farms are modern greenhouse technologies, education, extension, farming concentration, chemical utilization and ratio of rental land. Meanwhile, Tang et al. (2014) analyzed IE of 800 farmers in the Guanzhong Plain of China in the period 1999–2005 and found that mean irrigation water use efficiency for a period of 6 years is 15.77 %. Water price and disclosure of water use and water price management procedures affect water use efficiency positively. Second is data envelopment analysis (DEA) which is known as the nonparametric method. This method used to estimate irrigation water use efficiency in some studies, such as Ali and Klein (2014), Frija et al. (2009), Gadanakis et al. (2015), Speelman et al. (2008) and (Wang 2010). For example, Speelman et al. (2008) investigated 60 farms' water use efficiency in the north-west region of South Africa by using DEA and revealed that under constant and variable returns to scale, the mean efficiency of water use is 43 and 67 %, respectively, indicating that a considerable water loss could be avoided through removing inefficiency. The size of farm, land right, fragmentation, the feature of irrigation system, the selection of crop and irrigation methods had significant relationship with the efficiency of irrigation water. Using the same method, Gadanakis et al. (2015) evaluated the efficiency of water use of 66 horticulture farms in England. The author showed that the IE of the farms is 65 %; hence, 35 % reduction in water use could be achieved while maintaining the present output. The study also revealed that the factors having positive influence on water use efficiency are decision support tool, recycling water and the installation of trickle/drip/spray/lines irrigation. On the contrary, the negative affecting determinant is the use of overhead irrigation system.

SFA and DEA methods have partial advantage and disadvantage. Specifically, SFA differentiates the stochastic noise effects (weather condition, diseases, statistical noise, etc.) from inefficiency effects, but it requires specifying production function form and making distribution assumption for inefficiency term. Conversely, DEA cannot distinguish two above-mentioned effects and its estimation results are affected by the measurement errors and uncontrolled factors, but it does not have constraints on productive functional form specification and inefficiency term's distribution.

Since tea production is often affected by random factors outside farmers' control (weather, diseases, risk, etc.), we applied SFA for this study in order to separate this influence from inefficiency effect in measuring irrigation water use efficiency of Vietnamese tea production.

3 Empirical model and data

3.1 Estimating irrigation water use efficiency of tea production by stochastic frontier analysis

We suppose that a farm yields a quantity of fresh tea Y using inputs X (fertilizer, pesticide, labor, capital, other costs) and irrigation water W. The specific farm's stochastic production frontier function is:

$$Y_i = f(X_i, W_i, \alpha)\exp(\varepsilon_i \equiv v_i - u_i) \tag{2}$$

in which α represents unknown parameters and ε_i is the composed error term. Particularly, the term v_i denotes statistical noises and random factors (weather, natural disasters, luck, etc.), while the term u_i indicates the inefficiency effects.

On the basis of maximum likelihood estimation for Eq. (2), estimates of α, λ and σ were created. Where $\lambda = \sigma_u/\sigma_v$, $\sigma^2 = \sigma_u^2 + \sigma_v^2$.

Battese and Corra (1977) indicated that the parameter γ which investigates the determinant of the deviations from the frontier can be estimated as follows:

$$\begin{aligned} &\gamma = \sigma_u^2/\sigma^2 \\ &\text{Such that } 0 \leq \gamma \leq 1 \end{aligned} \tag{3}$$

If $\gamma = 0$, then all deviations are because of stochastic noises, while $\gamma = 1$ inefficiency effects are responsible for all deviations.

Jondrow et al. (1982) devised the specific farm's technical inefficiency calculation as follows:

$$E(u_i|\varepsilon_i) = \sigma^* \left[\frac{f^*(\varepsilon_i\lambda/\sigma)}{1 - F^*(\varepsilon_i\lambda/\sigma)} - \frac{\varepsilon_i\lambda}{\sigma}\right] \tag{4}$$

where E is the conditional mean of u_i given ε_i, $\sigma^{*2} = \sigma_u^2\sigma_v^2/\sigma^2$, f^* is normalized density function and F^* is distribution function.

In line with Reinhard et al. (1999), a flexible translog production frontier function was applied for IE measurement in this study. Equation (2) is written as follows:

$$\begin{aligned} \ln Y_i = {} & \alpha_0 + \alpha_w \ln W_i + \sum_{j=1}^{5} \alpha_j \ln X_{ij} + \frac{1}{2}\sum_{j=1}^{5}\sum_{k=1}^{5} \alpha_{jk} \ln X_{ij} \ln X_{ik} \\ & + \sum_{j=1}^{5} \alpha_{jw} \ln W_i \ln X_{ji} + \frac{1}{2}\alpha_{ww}(\ln W_i)^2 + v_i - u_i \end{aligned} \tag{5}$$

where Y_i represents the ith tea farm's output. The inputs consist of: (1) X_{i1}, fertilizer; (2) X_{i2}, pesticide; (3) X_{i3}, labor; (4) X_{i4}, capital (5) X_{i5}, other costs; and (6) W_i, irrigation water.

A farm gets irrigation water use efficiency when using minimum possible irrigation water denoted as W_i^F while conserving the actual output (Y_i). According to the constraint by Reinhard et al. (1999), an efficient irrigation water use farm is essentially to achieve TE ($u_i = 0$). Thus, production function of irrigation water efficient farm ith is given by:

$$\ln Y_i = \alpha_0 + \alpha_w \ln W_i^F + \sum_{j=1}^{5} \alpha_j \ln X_{ij} + \frac{1}{2}\sum_{j=1}^{5}\sum_{k=1}^{5} \alpha_{jk} \ln X_{ij} \ln X_{ik} + \sum_{j=1}^{5} \alpha_{jw} \ln W_i^F \ln X_{ji} + \frac{1}{2}\alpha_{ww}\left(\ln W_i^F\right)^2 + v_i \tag{6}$$

Setting Eqs. (5) and (6) equal, we obtain

$$\alpha_w \ln W_i + \sum_{j=1}^{5} \alpha_{jw} \ln W_i \ln X_{ji} + \frac{1}{2}\alpha_{ww}(\ln W_i)^2 - u_i = \alpha_w \ln W_i^F + \sum_{j=1}^{5} \alpha_{jw} \ln W_i^F \ln X_{ji} + \frac{1}{2}\alpha_{ww}\left(\ln W_i^F\right)^2 \tag{7}$$

Irrigation water use efficiency (IE) for ith tea farm is defined as:

$$\mathrm{IE}_i = \frac{W_i^F}{W_i} \tag{8}$$

where W_i^F is minimum possible quantity of irrigation water, W_i is real volume of irrigation water used.

Manipulating Eq. (8) results in

$$W_i^F = \mathrm{IE}_i \times W_i \qquad \text{So } \ln W_i^F = \ln \mathrm{IE}_i + \ln W_i \tag{9}$$

From Eqs. (7) and (9), we receive

$$\frac{1}{2}\alpha_{ww}(\ln \mathrm{IE}_i)^2 + \left(\alpha_w + \sum_{j=1}^{5} \alpha_{wj} \ln X_{ij} + \alpha_{ww} \ln W_i\right) \ln \mathrm{IE}_i + u_i = 0 \tag{10}$$

Solving quadratic Eq. (10), irrigation water use efficiency for specific tea farm ith can be got as:

$$\mathrm{IE}_i = \exp\left(\frac{-b_i \pm \sqrt{b_i^2 - 2\alpha_{ww} u_i}}{\alpha_{ww}}\right) \tag{11}$$

where $b_i = \alpha_w + \sum_{j=1}^{5} \alpha_{wj} \ln X_{ij} + \alpha_{ww} \ln W_i$. α_{ww} is the parameter estimated from translog frontier function (5).

According to Reinhard et al. (1999), in the condition of weak monotonicity, an efficient irrigation water use farm is also technical efficient, implying that irrigation water use efficiency is calculated by only using positive sign of Eq. (11).

3.2 Analyzing determinants of irrigation water efficiency

As farmers are final decision makers regarding to the utilization of irrigation water, the relationships among various socioeconomic farmers, specific farm characteristics and the efficiency of irrigation water use are necessary to be analyzed sufficiently. As the irrigation water use efficiency get values from 0 and 1, applying ordinary least square (OLS) to investigate the determinants of tea farms' irrigation water use efficiency would produce biased and inconsistent estimates (Greene 2003; Bravo-Ureta and Pinheiro 1997). Thus, Tobit regression model was employed in this research. The Tobit model is described as follow:

$$IE_i = \omega_0 + \sum_{s=1}^{16} w_{is} K_{is} + e_i \quad (12)$$

where IE_i is the irrigation water use efficiency score of the ith tea farm; K_{is} represents social and economic features of the ith farmers and tea farms including: age ($s = 1$), gender ($s = 2$), education ($s = 3$), ethnicity ($s = 4$), tea production experience ($s = 5$), cooperative participation ($s = 6$); household size ($s = 7$), tea age ($s = 8$), soil and water conservation practice ($s = 9$), agricultural income ($s = 10$), off-farm income share ($s = 11$), extension services access ($s = 12$), area ($s = 13$).

As an explanatory variable of irrigation water use efficiency, *water shortage awareness* variable ($s = 14$) is proposed. In keeping with Tang et al. (2013), a farmer perceived irrigation water scarcity if he/she undergoes the problem and understands that this scarcity may take place in the future.

In addition, since tea farms in the study site use three irrigation water sources (well, stream and public irrigation system), two dummy variables for water source were added: Well water ($s = 15$), Stream water ($s = 16$).

3.3 The procedure of data collection

The northern mountainous region is one of the poorest areas in Vietnam (GSO 2013). In recent years, tea cultivation has been the primary motivator of the region's economic growth. The region occupies 71.6 % national tea cultivation area and yields 64.7 % of total tea output (GSO 2013). Due to its geographically disadvantaged setting, the reduction in natural water in the northern mountainous region is more serious than in other regions (Vien 2011). The changing climate is also predicted to affect the north more than the south of Vietnam, which make serious drought and irrigation water shortage in the region (FAO 2011). Cook (2006) indicated that most of poor and food—insecure regions frequently lack water. Therefore, the northern mountainous region of Vietnam is a typical case to study IE at the micro level. Results and conclusions drawn from the study are useful for two reasons. First, these could serve as an important reference for other regions experiencing water shortage at present or in the future. Second, these are valuable for sustainable water management in Vietnam, particularly northern mountainous region since these could help guide policies toward higher irrigation water use efficiency.

Field survey was conducted in Thai Nguyen Province, which ranks first in tea production in the north region (GSO 2013) during the harvesting period of 2014. Cross-sectional data on tea production of 280 randomly tea growers were collected from four typical communes of Dong Hy District and Thai Nguyen City which are very well known for producing tea in Thai Nguyen Province.

Enumerators trained tea farmers in recording their productive activities and conducted face-to-face interviews with them using questionnaire that revised carefully after the pilot survey. During the survey, information regarding tea farm characteristics, amounts and value of tea output, quantities and costs of inputs, volume of water expended for tea production and irrigation practices of farmers was gathered. After data were checked, 37 tea farms were omitted from the analysis since their farming activities records are incompliance. The final sample for the analysis included 243 farms.

Table 1 Variables in production frontier model

Variables	Mean	SD	Min	Max
Fresh tea yield (kg/ha)	14,319.76	1340.90	10,028.64	17,740.02
Fertilizer (kg/ha)	1069.74	226.21	506.17	1768.52
Pesticide (L/ha)	120.82	23.30	62.95	200.00
Labor (man-day/ha)	398.05	132.11	169.75	976.86
Capital (thousand VND/ha)	2384.98	2238.39	164.99	17,045.00
Other cost (thousand VND/ha)	5072.08	708.89	3395.06	6983.02
Irrigation water (m^3/ha)	1580.46	556.11	429.98	3018.21

Source: Estimation of the authors

In the analysis, the total fresh tea yield was the output variable. Total output was measured in kilograms. Inputs considered were fertilizer measured in kilograms; pesticides measured in liters; labor measured in man days; irrigation water measured in m^3; capital consisting of machine expenses measured in thousand VND; and other costs in tea production measured in thousand VND. As land was considered the fixed factor in agricultural production, variables in this study were identified by per hectare terms in order to separate land and variable inputs.

Descriptive statistics of the variables in production frontier and Tobit model are given in Tables 1 and 2. Both stochastic production frontier model and Tobit regression model are estimated by STATA software version 11.

4 Results

4.1 Estimation of efficiency

Before estimating stochastic production frontier model, it is very essential to determine inputs that significantly affect output by using OLS (Bravo-Ureta and Pinheiro 1997). The OLS results show that *fertilizer*, *pesticide*, *labor*, *irrigation water* and *capital* have considerable relationship with tea output at 5 % level of significance, while the variable *other costs* was insignificant. As such, this variable was excluded from production model. Next, we tested multicollinearity which cause the estimation in the model biased using variance inflation factor. In addition, heteroskedasticity was also checked by using Breusch–Pagan/Cook–Weisberg test (Wooldridge 2012). The results show that there have no multicollinearity[2] and heteroskedasticity[3] in the model. Furthermore, we specified the production functional form. The Cobb–Douglas function (null hypothesis: H_0) against the translog function (alternative hypothesis: H_1) was tested using the log likelihood test (LR; Coelli et al. 2005). The LR test statistic was equal to 50.07 which is greater than $\chi^2_{(15,0.5)} = 31.31$; thus, Cobb–Douglas function form was rejected at 5 % level. With it, the translog production frontier model with five significant inputs (Eq. 5) was used in this study. The model was analyzed by maximum likelihood estimation (Table 3).

[2] Mean value of VIF is equal to 1.27.

[3] Prob > Chi-square = 0.8080, indicating that the null hypothesis of constant variance is accepted.

Table 2 Variables in Tobit model

Variables	Mean	SD	Min	Max
Age (year)	45.02	9.42	21	70.50
Gender (1 = male, 0 = female)	0.66	0.48	0	1
Education (year)	10.10	2.15	5	16
Ethnicity (1 = Kinh, 0 = otherwise)	0.20	0.40	0	1
Tea production experience (year)	19.74	9.38	5	50
Cooperative participation (1 = yes, 0 = no)	0.31	0.46	0	1
Household size (person)	4.36	1.10	2	8
Tea age (year)	14.86	7.72	3	36
Soil and water conservation practice (1 = yes, 0 = no)	0.41	0.19	0	1
Agricultural income (million VND/ha)	675.81	415.35	130.65	2574.20
Off-farm income share	0.08	0.13	0	0.59
Extension service access (1 = yes, 0 = no)	0.84	0.37	0	1
Area (ha)	0.26	0.14	0.05	0.6
Water shortage awareness (1 = if farmer recognizes problem in the field, 0 = otherwise)	0.18	0.39	0	1
Well water (1 = irrigating tea field by well water, 0 = otherwise)	0.50	0.50	0	1
Stream water (1 = irrigating tea field by stream water, 0 = otherwise)	0.15	0.36	0	1

Source: Estimation of the authors

The assumption that the tea farms in the study site were technically efficient was tested using z test. Following Coelli et al. (2005), we obtain $z_{\text{statistic}} = \frac{\tilde{\lambda}}{se(\tilde{\lambda})} = \frac{3.0906}{0.0140} = 220.76$. This test statistic exceeds the critical value $z_{0.99} = 2.334$; thus, the hypothesis was rejected at significant level of 1 %. The results also pointed that 90.48 % of the variance of output was due to inefficiency effects ($\gamma = 0.9048$).

Prior to estimate the irrigation water efficiency, the return to scale of existing tea production technology was considered. Table 4 reports the output elasticity per individual input.

The variable with the highest elasticity was *pesticide* (0.1229), followed by *irrigation water* (0.0754), *labor* (0.0679), *fertilizer* (0.0454) and *capital* (0.0125). *irrigation water* obtained an elasticity of 0.0754, suggesting that increase of 1 % in irrigation water leads to a corresponding increase of only 0.0754 % in the output. The sum of output elasticity (0.3241) is less than 1, indicating that Vietnamese tea production is under decreasing returns to scale.

Parameters from maximum likelihood estimation of translog production model (Table 3) were used to estimate irrigation water use efficiency (Eq. 11).

Table 5 shows that the average irrigation water use efficiency was 42.19 %. The efficiency levels considerably vary among tea farms, ranging from 2.02 to 93.33 %. The obtained mean efficiency level infers that the present output of tea farms probably conserved while using 57.81 % less irrigation water and fixing other inputs.

The cumulative distribution of the efficiency estimates indicates that all tea farms (100 %) achieved a TE greater than 50 %, and most farmers (59.26 %) achieved irrigation water use efficiency less than 50 %. Only about 4 % of those surveyed achieved irrigation

Table 3 MLE estimation of translog production frontier function

Variables	Coefficient	SE	Variables	Coefficient	SE
ln *W*	0.5325	0.6784	ln *L*·ln *C*	0.0015	0.0221
ln *F*	6.6397	1.6854	(ln *C*·ln *C*)/2	−0.0476	0.0111
ln *P*	−0.8866	0.9432	ln *W*·ln *F*	0.0352	0.0792
ln *L*	1.9573	0.8305	ln *W*·ln *P*	0.0637	0.0560
ln *C*	−0.3728	0.3250	ln *W*·ln *L*	−0.1090	0.0496
(ln *F*·ln *F*)/2	−1.0387	0.2307	ln *W*·ln *C*	−0.0263	0.0189
ln *F*·ln *P*	0.0281	0.1356	(ln *W*·ln *W*)/2	−0.0226	0.0553
ln *F*·ln *L*	−0.1118	0.0846	Constant	−18.6255	7.6709
ln *F*·ln *C*	0.1219	0.0393	σ_v	0.0337	0.0060
(ln *P*·ln *P*)/2	−0.0224	0.1876	σ_u	0.1042	0.0092
ln *P*·ln *L*	0.0579	0.0830	σ^2	0.0120	0.0017
ln *P*·ln *C*	0.0153	0.0307	$\lambda = \sigma_u/\sigma_v$	3.0906	0.0140
(ln *L*·ln *L*)/2	−0.1018	0.0768	$\gamma = \sigma_u^2/\sigma^2$	0.9048	

Source: Estimation of the authors

MLE maximum likelihood estimation, *F* fertilizer, *P* pesticide, *L* labor, *C* capital, *W* irrigation water, *SE* standard error

water efficiency higher than 80 %, suggesting that many tea farmers were low efficient water use.

4.2 The contributing factors of irrigation water use efficiency

The factors affect IE of tea farms are presented in Table 6. In Tobit models, R^2 ANOVA which is given by the ratio of estimated conditional mean variance to the observed variable variance is applied instead of the OLSs R^2 (Greene 2003). Results show that R^2 ANOVA = 0.4653, indicating that the model fit was satisfactory.

In consideration of contributing factors of irrigation water use efficiency, variables such as gender, water shortage awareness, soil and water conservation practice, off-farm income share, extension services access and well water were significant influence at the 1 and 5 % levels, while other variables were found to be insignificant impact. The variable *well water* negatively affects irrigation water use efficiency, whereas remaining variables had significantly positive impact on the efficiency level.

5 Discussion and policy recommendations

Climate change and water scarcity are just two of the challenges faced by the tea industry at present and in the coming years. Tackling these challenges requires the development and implementation of efficient irrigation systems that have high water use efficiency and are affordable for tea farmers. This paper analyzed the irrigation water use efficiency of 243 randomly Vietnamese tea farms and studied its determinants.

In the analysis, the mean irrigation water use efficiency was 42.19 %, indicating that the tea farms used irrigation water inefficiently. This interesting result shows that it is essential

Table 4 Output elasticity per specific input

Input	Fertilizer	Pesticide	Labor	Capital	Irrigation water	Sum
Elasticity	0.0454	0.1229	0.0679	0.0125	0.0754	0.3241

Source: Estimation of the authors

Table 5 Irrigation water use efficiency distribution of Vietnamese tea production

Efficiency score (%)	No. of farms	% of farms	Cumulative
≤50	144	59.26	59.26
50–60	31	12.76	72.02
60–70	34	13.99	86.01
70–80	24	9.88	95.88
80–90	9	3.70	99.59
≥90	1	0.41	100.00
Total	243	100.00	
Mean		42.19	
Min		2.02	
Max		93.33	

Source: Estimation of the authors

to promote IE of tea production amid climate change which is not mentioned in the literatures (Basnayake and Gunaratne 2000; Nghia 2008; Saigenji and Zeller 2009; Baten et al. 2010; Haridas et al. 2012). The reason for low efficiency of water use in tea production might be the unsuitable price mechanism on irrigation water in Vietnam. Currently, the farmers' water consumption in Vietnam at small-scale irrigation scheme is supported. Since 2008, the government has implemented an irrigation fee exemption policy for agricultural production (Decree. No 115/2008/ND-CP). While there is success in supporting farmers to reduce production cost, the policy also has some disadvantages. For

Table 6 Tobit model estimates on determinants of irrigation water use efficiency

Variables	Coefficient	Variables	Coefficient
Gender	0.1914***	Tea experience production	0.0012
Water shortage awareness	0.1359***	Cooperative participation	0.0331
Soil and water conservation practice	0.0245***	Household size	0.0006
Off-farm income share	0.1960**	Tea age	−0.0018
Extension services access	0.1092**	Agricultural income	−0.0118
Well water	−0.0973***	Area	−0.0634
Age	0.0003	Stream water	−0.0468
Education	−0.0003	Constant	0.1689
Ethnicity	0.0158	R^2 ANOVA	0.4653

Source: Estimation of the authors

*** and ** represent significant level of 1 and 5 %

instance, it reduces farmer's responsibility in the management, protection and consumption of water. As a result, farmers have little economic stimulus to use water efficiently or to apply the irrigation technologies that save water. Therefore, re-imposing proper irrigation fee in the future can probably prompt tea farmers to use water more efficiently. This direction is discussed by Tang et al. (2014) who found that higher price can increase water use efficiency which sustain long-term agricultural production. Another implication of low irrigation water use efficiency is that 57.81 % reduction in water use for tea production can be attained with the present state of technology while maintaining observed output. With increasing the present irrigation water use efficiency of tea production, a significant portion of the water could be reallocated to other sectors, significantly reducing pressure on water resource in the study site. This result is very suitable with Hong and Yabe (2015) who found that Vietnamese tea farms have a great chance to save input utilization under the existing productive technologies.

The relationship among irrigation water use efficiency and various attributes of tea farms and farmers was then analyzed. Results of Tobit model showed that gender, water shortage awareness, soil and water conservation practice, off-farm income share, extension services access and well water have a significant impact on IE.

Farmer's gender affected irrigation water efficiency positively. Male farmers used irrigation water more efficient than female counterparts. The popular reasons for discrepancy in agricultural water resource management between men and women are social gender labor division and gender norms, which women are assigned a lot of water-related duties, whereas men are given most water-related powers and rights (Zwarteveen 1997; Van Koppen 1998; Singh et al. 2006; IFAD 2007). This study results thus corroborated the fact that there are persisting problems regarding women involvement in water management. Although women in the study site undertake a lot of work in tea production, their rights to access productive resources, particularly water, remain limited due to lacking acknowledge their role. Furthermore, while the majority of water users are women, only men are trained and learned techniques on operation, maintenance and how to use irrigation systems efficiently. Thus, men become more skillful in these aspects than women. In conclusion, Vietnamese policy-makers should raise awareness on the role of women in agricultural production in general and in water use in particular, and address their unequal access to water as well as productive resources, extension services and decision-making spheres related to water management. This can potentially improve livelihoods and reduce water wastage in poor rural areas.

The results also revealed that the perception or acknowledgment of water scarcity has a considerably positive impact on IE. This means that the farmers who recognize the insufficiency of water seemed to use it more efficient than the others which is also indicated in the study of Tang et al. (2013). This finding suggests that disseminating the water scarcity to tea farmers is very an important policy targeting their behavior change toward efficient water use.

Other significant variable *soil and water conservation practice* had positively affect water use efficiency. This result shows that it is very essential to widen soil and water conservation practices in tea farms to improve IE.

It was found that the estimated coefficient of *off-farm income share* also positively affects irrigation water efficiency. This suggests that a rise in off-farm income would encourage farmers to invest more in advanced irrigation technologies, which leads to a more efficient water use.

Moreover, the study confirms the significance of agricultural extension services in increasing the TE of tea production as asserted by von Bülow and Sørensen (1993), Iqbal et al. (2006) and Saigenji and Zeller (2009). Vietnamese extension program aims to support agriculture production develop sustainably, in general, and tea production, in particular. Farmers can broaden their knowledge about land preparation, planting and practicing soil and water conservation techniques through extension program. Thus, the improvement in extension services access can help Vietnamese tea farmers optimize TE, particularly water use.

Meanwhile, the dummy for well irrigation exhibited a negative impact on irrigation water use efficiency, implying that farms that use well water irrigation are less efficient than those using water from public system. The reason for this problem is that a price is charged for the latter, which is also reported by Karagiannis et al. (2003). Furthermore, well irrigation method which has two typical characteristics such as flexible irrigation time, short distance of water delivery might lead to farmers using water less efficiently. These findings suggest that water conservation could be achieved through better management. Specifically, imposing an irrigation water fee and utilizing suitable irrigation systems are an important issue in putting into practice better water management.

6 Conclusion

This study investigates irrigation water use efficiency of Vietnamese tea production using economic method—SFA. The tea farmers were found to be inefficient irrigation water consumption. The low water use efficiency estimate (42.19 %) suggests that a 57.81 % reduction in current water use for tea production could be achieved given existing technology, without compromising output. Therefore, further improvement in irrigation water use efficiency is indispensable to tea production in Vietnam under context of climate change and water scarcity.

The relationship among irrigation water use efficiency and tea farmer and farm attributes is analyzed by Tobit model. We found that gender, water scarcity perception, soil and water conservation, non-agricultural income share and extension service positively affect the efficiency of irrigation water use, while using irrigation water from well has negative influence on it. To increase water use efficiency, the government should ensure equitable right to use water, trainings and involvement in water management for female farmers. Furthermore, it is essential for the government to initiate the dissemination of information on water scarcity to farmers, promote the application of soil and water conservation techniques in tea farms, strengthen extension services and advocate the appropriate use of irrigation systems for better water management.

Acknowledgments This research was funded in 2014 by the Monbukagakusho scholarship (Study Number 26310311), the Japanese Ministry of Education, Culture, Sports, Science, and Technology and the Setsutaro Kobayashi Memorial Fund. The authors are thankful to the anonymous reviewers for their appreciated recommendations and comments on the manuscript.

Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest.

References

Ahmed, S., Stepp, J. R., Orians, C., Griffin, T., Matyas, C., Robbat, A., Cash, S., Xue, D., Long, C., & Unachukwu, U. (2014). Effects of extreme climate events on tea (*Camellia sinensis*) functional quality validate indigenous farmer knowledge and sensory preferences in tropical china. *PLoS ONE*, *9*(10), e109126. doi: 10.1371/journal.pone.0109126.

Aigner, D., Lovell, C. K., & Schmidt, P. (1977). Formulation and estimation of stochastic frontier production function models. *Journal of Econometrics, 6*(1), 21–37.

Ali, M. K., & Klein, K. (2014). Water use efficiency and productivity of the irrigation districts in Southern Alberta. *Water Resources Management, 28*(10), 2751–2766.

Allan, T. (1999). Productive efficiency and allocative efficiency: Why better water management may not solve the problem. *Agricultural Water Management, 40*(1), 71–75.

Atkinson, S. E., & Cornwell, C. (1994). Estimation of output and input technical efficiency using a flexible functional form and panel data. *International Economic Review*, *35*(1), 245–255. doi:10.2307/2527100

Barker, R., Dawe, D., & Inocencio, A. (2003). Economics of water productivity in managing water for agriculture. In J. W. Kijne, R.Barker, D. Molden (Eds.), *Water productivity in agriculture: Limits and opportunities for improvement* (pp. 19–35). Wallingford: CAB International.

Basnayake, B., & Gunaratne, L. (2000). Estimation of technical efficiency and it's determinants in the tea small holding sector in the Mid Country Wet Zone of Sri Lanka. *Economics, 4*(Part 1), 137–150.

Baten, A., Kamil, A. A., & Haque, M. A. (2010). Productive efficiency of tea industry: A stochastic frontier approach. *African Journal of Biotechnology, 9*(25), 3808–3816.

Battese, G. E., & Corra, G. S. (1977). Estimation of a production frontier model: With application to the pastoral zone of Eastern Australia. *Australian Journal of Agricultural Economics, 21*(3), 169–179. doi:10.1111/j.1467-8489.1977.tb00204.x.

Billi, A., Canitano, G., & Quarto, A. (2007). The Economics of water efficiency: A review of theories, measurement issues and integrated models. *Water Use Efficiency and Water Productivity - Proceedings of 4th WASAMED (WAter SAving in MEDiterraneanagriculture) Workshop Amman (Jordan), 30 Sept–4 Oct, 2005*, 231–269.

Bravo-Ureta, B. E., & Pinheiro, A. E. (1997). Technical, economic, and allocative efficiency in peasant farming: Evidence from the Dominican Republic. *The Developing Economies, 35*(1), 48–67. doi:10.1111/j.1746-1049.1997.tb01186.x.

Brouder, A. M., Billing, S., & Uren, S. (2014). *The future of tea: A hero crop for 2030*. Tea 2030 steering group.

Chang, K. (2015). *World tea production and trade: Current and future development*. Food and Agriculture Organization of United Nation.

Coelli, T., Rahman, S., & Thirtle, C. (2002). Technical, allocative, cost and scale efficiencies in Bangladesh rice cultivation: A non-parametric approach. *Journal of Agricultural Economics, 53*(3), 607–626.

Coelli, T. J., Rao, D. S. P., O'Donnell, C. J., & Battese, G. E. (2005). *An introduction to efficiency and productivity analysis*. New York: Springer Science & Business Media.

Cook, S. (2006). *Agricultural water productivity: Issues, concepts and approaches*. International Water Management Institute.

Dhehibi, B., Lachaal, L., Elloumi, M., & Messaoud, A. (2007). Measuring irrigation water use efficiency using stochastic production frontier: An application on citrus producing farms in Tunisia. *African Journal of Agricultural and Resource Economics, 1*(2), 1–15.

Dutta, R. (2014). Climate change and its impact on tea in Northeast India. *Journal of Water and Climate Change, 5*(4), 625–632.

FAO. (2011). *Strengthening capacities to enhance coordinated and integrated disaster risk reduction actions and adaptation to climate change in agriculture in the Northern mountain regions of Vietnam.*

Färe, R. L. C. K. (1978). Measuring the technical efficiency of production. *Journal of Economic theory, 19*(1), 150–162.

Farrell, M. J. (1957). The measurement of productive efficiency. *Journal of the Royal Statistical Society. Series A (General)*. doi:10.2307/2343100.

Frija, A., Chebil, A., Speelman, S., Buysse, J., & Van Huylenbroeck, G. (2009). Water use and technical efficiencies in horticultural greenhouses in Tunisia. *Agricultural Water Management, 96*(11), 1509–1516.

Gadanakis, Y., Bennett, R., Park, J., & Areal, F. J. (2015). Improving productivity and water use efficiency: A case study of farms in England. *Agricultural Water Management, 160*, 22–32.

Gans, J., King, S., Stonecash, R., & Mankiw, N. G. (2011). *Principles of economics*. Cengage Learning Australia Pty Limited.

Giang, P. Q., Toshiki, K., Kunikane, S., & Sakata, M. (2012). Integrated water resources management in Vietnam under the challenges of climate change. *Environment and Natural Resources Journal, 10*(1), 28–41.

Gleick, P. H. (1993). *Water in crisis: A guide to the world's fresh water resources*. Oxford University Press, Inc.

Greene, W. H. (2003). Simulated likelihood estimation of the normal-gamma stochastic frontier function. *Journal of Productivity Analysis, 19*(2–3), 179–190.

GSO. (2011). *Statistical year book of Vietnam*. Hanoi: General statistic office, Statistical Publishing House.

GSO. (2013). *Planted tea area by province*. Vietnamese General statistic office http://fsiu.mard.gov.vn/data/trongtrot.htm.

GSO. (2014). *Major exported commodities in 2014*. Vietnamese General statistic office https://www.gso.gov.vn/default.aspx?tabid=629&ItemID=15484.

Haridas, N., Kumar, S. A., Nerella, V. K., Deepika, M., & Jyotishi, A. (2012). *Measuring technical efficiency in tea plantations in India: A panel data analysis*. Discussion paper.

Hong, N. B., & Yabe, M. (2015). Resource use efficiency of tea production in Vietnam: Using translog SFA model. *Journal of Agricultural Science, 7*(9), 160.

IFAD. (2007). *Gender and water securing water for improved rural livelihoods: The multiple-uses system approach*. International Fund for Agricultural Development.

Iqbal, S., Ireland, C., & Rodrigo, V. (2006). A logistic analysis of the factors determining the decision of smallholder farmers to intercrop: A case study involving rubber–tea intercropping in Sri Lanka. *Agricultural Systems, 87*(3), 296–312.

Jondrow, J., Lovell, C. K., Materov, I. S., & Schmidt, P. (1982). On the estimation of technical inefficiency in the stochastic frontier production function model. *Journal of Econometrics, 19*(2), 233–238. doi:10.1016/0304-4076(82)90004-5.

Kabubo-Mariara, J., & Karanja, F. K. (2007). The economic impact of climate change on Kenyan crop agriculture: A Ricardian approach. *Global and Planetary Change, 57*(3), 319–330.

Karagiannis, G., Tzouvelekas, V., & Xepapadeas, A. (2003). Measuring irrigation water efficiency with a stochastic production frontier. *Environmental & Resource Economics, 26*(1), 57–72.

Kopp, R. J. (1981). The measurement of productive efficiency: A reconsideration. *The Quarterly Journal of Economics*, *96*(3), 477–503.

Krechowicz, D., Venugopal, S., Sauer, A., Somani, S., & Pandey, S. (2010). *Weeding risk: Financial impacts of climate change and water scarcity on Asia's food and beverage sector*. The World Resources Institute, 10 G Street, NE Suite 800 Washington, D. C. 20002 USA.

McGuckin, J. T., Gollehon, N., & Ghosh, S. (1992). Water conservation in irrigated agriculture: A stochastic production frontier model. *Water Resources Research, 28*(2), 305–312.

Molden, D., Oweis, T., Steduto, P., Bindraban, P., Hanjra, M. A., & Kijne, J. (2010). Improving agricultural water productivity: Between optimism and caution. *Agricultural Water Management, 97*(4), 528–535.

Nghia, T. D. (2008). *An analysis of economic and environmental impacts for the transition to organic tea production in the Thai Nguyen province of Vietnam*.

Pereira, L. S., Cordery, I., & Iacovides, I. (2009). *Coping with water scarcity: Addressing the challenges* (382 pp). Dordrecht: Springer Science & Business Media.

Pereira, L. S., Cordery, I., & Iacovides, I. (2012). Improved indicators of water use performance and productivity for sustainable water conservation and saving. *Agricultural Water Management, 108*, 39–51.

Reinhard, S., Lovell, C. K., & Thijssen, G. (1999). Econometric estimation of technical and environmental efficiency: An application to Dutch dairy farms. *American Journal of Agricultural Economics, 81*(1), 44–60. doi:10.2307/1244449.

Rockström, J., & Barron, J. (2007). Water productivity in rainfed systems: Overview of challenges and analysis of opportunities in water scarcity prone savannahs. *Irrigation Science, 25*(3), 299–311.

Saigenji, Y., & Zeller, M. (2009). *Effect of contract farming on productivity and income of small holders: The case of tea production in north-western Vietnam.* Accessed January 10, 2012.

Scheierling, S. M., Treguer, D. O., Booker, J. F., & Decker, E. (2014). *How to assess agricultural water productivity? Looking for water in the agricultural productivity and efficiency literature (July 1, 2014).* World Bank Policy Research Working Paper (6982).

Schoengold, K., & Zilberman, D. (2007). The economics of water, irrigation, and development. *Handbook of Agricultural Economics, 3*, 2933–2977.

Seckler, D., Molden, D., & Sakthivadivel, R. (2003). The concept of efficiency in water resources management and policy. In J. W. Kijne, R. Barker, D. Molden (Eds.), *Water Productivity in Agriculture: Limits and Opportunities for Improvement* (pp. 37–51). Wallingford: IWMI and CABIPubl.

Sharma, B., Molden, D., & Cook, S. (2015). Water use efficiency in agriculture: Measurement, current situation and trends. In P. Drechsel, P. Heffer, H. Magen, R. Mikkelsen, D. Wichelns (Eds.), *Managing Water and Fertilizer for Sustainable Agricultural Intensification*. Paris: International Fertilizer Industry Association (IFA), International Water Management Institute (IWMI), International Plant Nutrition Institute (IPNI) and International Potash Institute (IPI).

Singh, N., Jacks, G., Bhattacharya, P., & Gustafsson, J. E. (2006). Gender and water management: Some policy reflections. *Water Policy, 8*(2), 183–200.

Speelman, S., D'Haese, M., Buysse, J., & D'Haese, L. (2008). A measure for the efficiency of water use and its determinants, a case study of small-scale irrigation schemes in North-West Province, South Africa. *Agricultural Systems, 98*(1), 31–39.

Szenthe, A. (2015). *The Worlds top 10 tea producing nations*. Worldatlas http://www.worldatlas.com/articles/the-worlds-top-10-tea-producing-nations.html.

Tang, J., Folmer, H., Vlist, A. J., & Xue, J. (2014). The impacts of management reform on irrigation water use efficiency in the Guanzhong plain, China. *Papers in Regional Science, 93*(2), 455–475.

Tang, J., Folmer, H., & Xue, J. (2013). Estimation of awareness and perception of water scarcity among farmers in the Guanzhong Plain, China, by means of a structural equation model. *Journal of Environmental Management, 126*, 55–62.

Van Halsema, G. E., & Vincent, L. (2012). Efficiency and productivity terms for water management: A matter of contextual relativism versus general absolutism. *Agricultural Water Management, 108*, 9–15.

Van Koppen, B. (1998). Water rights, gender, and poverty alleviation. Inclusion and exclusion of women and men smallholders in public irrigation infrastructure development. *Agriculture and Human Values, 15*(4), 361–374.

Viaggi, D., Zanni, G., & Raggi, M. (2014). Changing perspectives on the economics of water. *Water, 6*(10), 2969–2977.

Vien, T. D. (2011). Climate change and its impact on agriculture in vietnam. *Journal ISSAAS, 17*(1), 17–21.

Vietnam irrigation and drainage profile. (2015). http://www.fao.org/nr/water/aquastat/countries_regions/Profile_segments/VNM-IrrDr_eng.stm.

VietnameseTeaAssociation. (2009). *General report on tea sector*.

von Bülow, D., & Sørensen, A. (1993). Gender and contract farming: Tea outgrower schemes in Kenya. *Review of African Political Economy, 20*(56), 38–52.

Wang, X.-Y. (2010). Irrigation water use efficiency of farmers and its determinants: Evidence from a survey in Northwestern China. *Agricultural Sciences in China, 9*(9), 1326–1337.

Watto, M. A., & Mugera, A. W. (2015). Econometric estimation of groundwater irrigation efficiency of cotton cultivation farms in Pakistan. *Journal of Hydrology: Regional Studies, 4*, 193–211.

Wichelns, D. (2014). Do estimates of water productivity enhance understanding of farm-level water management? *Water, 6*(4), 778–795.

Wijeratne, M., Anandacoomaraswamy, A., Amarathunga, M., Ratnasiri, J., Basnayake, B., & Kalra, N. (2007). Assessment of impact of climate change on productivity of tea (*Camellia sinensis* L.) plantations in Sri Lanka. *Journal of the National Science Foundation of Sri Lanka, 35*(2), 119–126.

Wooldridge, J. (2012). *Introductory econometrics: A modern approach*. USA: Cengage Learning.

Zhang, Y., Kendy, E., Qiang, Y., Changming, L., Yanjun, S., & Hongyong, S. (2004). Effect of soil water deficit on evapotranspiration, crop yield, and water use efficiency in the North China Plain. *Agricultural Water Management, 64*(2), 107–122.

Zwarteveen, M. Z. (1997). Water: From basic need to commodity: A discussion on gender and water rights in the context of irrigation. *World Development, 25*(8), 1335–1349.