Will Farmers Save Water? A Theoretical Analysis of Groundwater Conservation Policies for Ogallala Aquifer

Tong Wang
Assistant Professor and Extension Specialist
Department of Economics
South Dakota State University
Brookings, SD 57007

Seong C. Park
Associate Professor
Department of Agricultural Economics
Texas A&M AgriLife Research
Vernon, TX 76385

Hailong Jin
Instructor
College of Business and Natural Sciences
Black Hills State University
Spearfish, SD 57783

***Selected Paper prepared for presentation at the Southern Agricultural Economics Association Annual Meeting, San Antonio, Texas, February 6*-9 2016**

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Abstract

A variety of water conservation policy alternatives have been promoted to extend the economic life of Ogallala Aquifer in the Southern Great Plains. However, few studies have been done to analyze whether these policies provide profit-driven farmers with incentives to save water. In this paper we adopt a theoretical approach to analyze farmer's optimal response when facing following policy alternatives, including 1) irrigation technology subsidy, 2) increased water cost, 3) unit subsidies for water saving; and 4) subsidies on water-conservative crop. Our findings suggest that optimal water conservation policies vary by region. Specifically, the switching to higher efficiency technology should occur in a preventative stage for the water saving to occur. Similarly, an increase in water cost promotes water saving only when water resource is relatively abundant. In regions where groundwater already poses a constraint, the unit subsidy for actual water saved and price subsidy for water-conservative crops are more effective in achieving the water conservation goal.

Keywords: Ogallala Aquifer, water conservation, economic incentive, irrigation technology, subsidy, water cost.

1. Introduction

As one of the world's largest underground freshwater sources, Ogallala Aquifer encompasses 174,000 square miles and underlies parts of eight states from the Texas panhandle to South Dakota (Alley, Riley and Franke, 1999). First discovered by the United States Geological Survey (USGS) in the 1890s, Ogallala Aquifer has very limited use in the early years due to the expensive and inefficient pumping facilities (Weakly, 1932; Brackett and Lewis, 1933; Weakly, 1936). From the 1950s and forward Ogallala groundwater used for irrigation purpose increased substantially, owing to the improved pumping and the irrigation technologies (Hornbeck and Keskin, 2012). However, the recharge of Ogallala Aquifer is minimal compared to the rate of depletion, due to predominantly semiarid environment of the high plains and low infiltration of surface water (Zwingle 1993; Opie 1993; Birkenfeld, 2003; McGuire et al. 2003). Based on USGS estimates, between 1949 and 1974 the water tables declined dramatically as the water withdrawals quintupled (McGuire et al. 2003, Little 2009).

Among the eight states underlying the aquifer, groundwater depletion rates vary greatly. According to Evett et al. (2014), between 1980 and 2007 Nebraska has the smallest depletion rates of only 1%, while Texas High Plains, where the aquifer is the only source of irrigation water, has the largest depletion rate of 35.9%, followed by New Mexico and Kansas with the depletion rates of 20.6% and 19.7% respectively. With groundwater used intensively for crop irrigation, rapid groundwater level decline in southern portion of the Ogallala Aquifer is an on-going concern (Almas, Colette and Park, 2006; Wheeler, 2008). Serious implications could occur for the regional economic viability in the future if the current depletion rates continue (Amosson et al., 2009). For example, Ashworth (2006) estimated that on the depletion of the aquifer more than $20 billion worth of food and fiber would disappear.

As a result, the focus on aquifer irrigation has shifted from economic development and expansion in the 1950s and 1960s to water conservation issues in the most recent two decades. (Grubb 1966; Osborn and McCrary 1972; Musick et al 1990; Amosson et al 2001; Colette, Robinson, and Almas 2001). Policy makers and stakeholders are investing on different water conservation policy alternatives to extend the economic life of Ogallala aquifer. As over 95% of the water withdrawals are used for irrigation within Southern High Plains region of Texas and Eastern New Mexico, agriculture is inevitably the main target for potential water conservation (HDR Engineering, Inc., 2001).

Possible water conservation policy alternatives include voluntary interventions that are supported by the Environmental Quality Incentive Program (EQIP) funds. Provided by Natural Resources Conservation Service, EQIP offers incentive payments for farms that adopt the potential water conservation practices. Among EQIP sponsored interventions, subsidy for advanced irrigation technology adoption and water right buyout programs, either permanent or temporary, are among the most studied examples (Wheeler et al., 2008; Amosson et al., 2009). Compared to voluntary interventions, the possible has not yet been implemented by most water districts, though some of them are already authorized by state legislation. Examples include two mandates evaluated by Johnson et al. (2006): 1) a water pumpage fee of $ 1 per acre foot; and 2) the 50/50 quota policy that restricts the water use to ensure that 50% of the current saturated thickness remains over the 50-year planning horizon. Tewari et al. (2014) studied the potential effects of the multi-year water allocation program, which is to achieve equitable distribution of the limited groundwater, coupled with water-use restriction. According to Weinheimer et al. (2013), interventions on commodity and energy prices may also incentivize farmers to conserve water through economic incentives.

To evaluate the impact of policy alternatives on Ogallala water conservation potential, the aforementioned literature has unanimously adopted the framework of the "Ogallala Model" (Weinheimer et al. 2013). It was first developed by Feng (1992), and later on modified by Arabiyat (1998), Das (2004), Johnson (2003), Terrell (1998), Wheeler (2004), Weinheimer (2008), to name quite a few. This is a non-linear dynamic economic optimization approach that utilizes crop yield functions, crop acreages, cost and hydrologic conditions to estimate the optimal crop combination and water use for certain county or region over a long term planning horizon, usually 60 years. From a social planner's perspective, Ogallala Model provides the long-term optimal solution when facing the depleting water resource, which can be used to compare the social optimal consequences under each policy alternatives.

While Ogallala Model predicts the future depletion rate of Ogallala Aquifer best achievable by the social planner, in reality water conservation only occurs with a reduction in individual farmer's irrigation water usage. As pointed out by Brill and Burness (1994), there can be large divergence between the competitive and social optimal rates of groundwater pumping with declining well yields, which is true for Ogallala Aquifer with wells yield declining from 1000 to 1200 gallons per minute in the 1960's to less than 200 gallons per minute in the 1990's (Almas, Colette and Park, 2006). In addition, unlike social planners the farmers tend to make myopic decision in response to current period output prices and input costs without considering the long-term profit consequences (Huffaker, 2008; Hendricks and Peterson, 2012). Asymmetric information and adverse selection may further diminish of the effectiveness of water conservative policies. As pointed out by Pfeiffer and Lin (2009), farmers tend to enroll their least productive land in the water right buyout program. Thus the program's effectiveness in water conservation is greatly compromised as much of the enrolled land initially did not use much irrigation water. In states such as Texas where the Rule of Capture remains the primary law (Wheeler, 2008), the landowners are accustomed to the right to extract water underlying his property. Therefore the implementation of mandatory programs that limits the use of water might be met with harsh resistance. With an overarching regional planning model such key behavior issues are generally overlooked.

As a result, it is necessary to identify from the farmer's perspective the effective policy alternatives that achieve the social goal of water conservation. Compared to the literature using Ogallala Model approach, few studies has done to analyze farmer's behavioral responses to various policy alternatives, two notable exceptions are Huffaker and Whittlesey (2003) and Huffaker (2008). However, regional and farm characteristics are not accounted for in these studies. In addition, current theoretical papers only focus the single-crop scenario, but have in general neglected the multi-crop scenario. Furthermore, the consequences of some potential policy alternatives such as water right buyout program and subsidy to water-conservation crop has not yet been studied. Due to these limitations, many questions remain unanswered by the existing conceptual models. For example, will the policy alternative successful in one region remain effective in another region? Besides water adjustment at intensive margin[1], how will water use be adjusted at extensive margin in response to potential policy alternatives? Our paper intends to shed some fresh insights on these questions.

In this paper we extend the work of Huffaker and Whittlesey (2003) and Huffaker (2008) to analyze the optimal water use adjustments by a representative farmer in response to several

[1] Similar to existing literature(e.g., Moore, Gollehon and Carey, 1994; Hendricks and Peterson, 2012) , here water adjustment at intensive margin refers to the water use change on the existing crops; while water adjustment at extensive margin refers to water use change caused by land allocation decision.

potential policy alternatives, including: 1) irrigation technology subsidy, 2) increased water cost, 3) subsidies for water saving, which in extreme case, is comparable to the water right buyout program, and 4) subsidies on water-conservative crop. We point out the regional differences may affect the success of these policy alternatives in such a way that a policy works well in one area may not work in another. In addition, for the farmer to make optimal decisions that achieves both profit increase and water saving, a single policy tool sometimes falls short. A combination several policy tools may provide a solution to achieve the dual objectives.

2. Modeling

In this section we will model two scenarios: 1) the farmer only grows one type of crop and 2) the farmer can chose between two crops. The purpose of including the two-crop scenario is to investigate the potential water demand change at extensive margin and the proper policy tools that can aid in achieving this purpose.

2.1. Single-Crop Scenario

First we introduce the crop yield function. Suppose the maximum crop yield is Y_m which is obtainable at evapotranspiration (ET) rate of E_m, referred to as the satiation ET level. Given the crop type, we assume that Y_m and E_m are fixed parameters. Suppose the irrigation efficiency is $\xi \in (0,1]$, defined as the percentage of total irrigation that is used to satisfy the crop's ET demand. The cost to increase efficiency rate ξ by one unit is $C(\xi)$, an increasing and convex function of ξ. At the efficiency rate of ξ, to achieve the satiation ET of E_m, the real water usage required by farmer is $W_m = E_m / \xi$, which is defined as the satiation water use. We can see given the crop type, satiation water use declines with irrigation efficiency. We assume the crop yield function as $Y = Y(W, \xi)$, which is concave w.r.t. both the water application level, W and the irrigation efficiency level, ξ.

2.1.1. Subsidy on Irrigation Technology Investment

Different from Huffaker (2008), who assumed that farmers choose irrigation technology and water use amount simultaneously, we model the farmer's choice when facing a subsidy on irrigation technology investment as a two-step decision problem. First, the farmer chooses the irrigation technology; Second, based on the chosen irrigation technology the farmer further choose the profit-maximizing water usage, W.

Backward induction approach is used to solve the two-stage problem. First we solve the optimal water usage problem at the second stage. Assume the irrigation technology is given as ξ, the farmer will choose the optimal level of water usage $W(\xi)$ to maximize the profit:

$$\max_W \pi = \max_W PY(W, \xi) - C_w W \quad (1)$$

Here we assume the farmer takes the market price P as given. The water price, denoted as C_w, refers to the pumping cost, as farmers in Kansas and Texas do not pay for water but incur a cost from the energy required to pump the water (Wheeler,2008; Hendricks and Peterson, 2012). The first order condition (FOC) for objective function (1) is:

$$\frac{\partial \pi}{\partial W} = P \frac{\partial Y}{\partial W}(W(\xi), \xi) - C_w = 0 \quad (2)$$

To check how the change of ξ alters the optimal value of water use, W^*, we take a total derivation w.r.t. ξ on the FOC condition (2)[2]:

$$P\frac{\partial^2 Y}{\partial W^2}(W^*,\xi)\frac{\partial W}{\partial \xi}+P\frac{\partial^2 Y}{\partial W \partial \xi}(W^*,\xi)=0 \tag{3}$$

From (3) we can readily obtain:

$$\frac{\partial W}{\partial \xi}=-\frac{\frac{\partial^2 Y}{\partial W \partial \xi}(W^*,\xi)}{\frac{\partial^2 Y}{\partial W^2}(W^*,\xi)} \tag{4}$$

Similar to the finding of Huffaker (2008), it is obvious from Equation (4) that whether water saving occurs with a more efficient irrigation technology depends on the sign of cross partial derivative function, $\frac{\partial^2 Y}{\partial W \partial \xi}$, or how the improvement in irrigation technology affect the marginal product of water. The sign of Equation (4) could be analyzed with the aid of Figure 1, which depicts crop revenue function curves $PY(W,\xi)$ under two irrigation efficiency levels, ξ^L and ξ^H. Compared to the low-efficiency curve, the high-efficiency curve is initially associated with higher marginal value product (MVP) of water, which gradually declines to zero at the high-efficiency satiation water use point $W_H^m = E_m / \xi_H$. The MVP of water for low-efficiency curve also declines until it reaches zero at the low-efficiency satiation water use point $W_L^m = E_m / \xi_L$, which is greater than W_H^m. Then we can prove the following result[3]:

[2] Here we assume the efficiency rate is continuous as in Huffaker (2008).
[3] Without further mentioning, all necessary proofs of the results in this paper are provided in the Supplemental Appendix.

Result 1: There exists a threshold water pumping cost $\overline{C_w}$, at which the marginal value products of water are equal under high and low efficiency technology, as demonstrated by $PY_w(\overline{W}, \xi^H) = PY_w(\overline{W}, \xi^L) \equiv \overline{C_w}$[4].

Based on the threshold water cost of $\overline{C_w}$ established in Result 1, we can further check the water conservation potential of improved irrigation efficiency under two different water cost levels, C_w^H and C_w^L. First, suppose the water cost is $C_w^H > \overline{C_w}$. From Figure 1 we can see under the low irrigation efficiency, optimal water use is W_L^*, while at the high irrigation efficiency, optimal water use increased to W_H^*. Therefore water saving does not occur in this scenario, instead more water is used as indicated by the direction of the red arrow; Next, suppose the water cost is $C_w^L \leq \overline{C_w}$, then at the high irrigation efficiency, the optimal water use is $W_H^{*\prime}$, which is lower than $W_L^{*\prime}$, the optimal water use under the low irrigation efficiency. Therefore water saving occurs in this scenario, as illustrated by the direction of the green arrow. This finding can therefore be summarized as:

Result 2: As long as the water cost is below $\overline{C_w}$, water saving will occur with the enhanced irrigation technology. On the contrary, if the water cost is above $\overline{C_w}$, then water usage will increase.

Result 2 implies the sign of Equation (4) could be either way, contingent on the water cost. Intuitionally we can understand it in the following way: when the water cost is low, the

[4] Note that Y_W stands for $\partial Y / \partial W$.

profit maximizing irrigation level is likely close to the satiation water use. Advancement in irrigation technology can help farmers lower water usage as the extra water usage serves no good after reaching the satiation water use, which is lower under new technology. However, when the water cost is relatively high, the farmers most probably already grow the crop under a stress irrigation level, with a much lower yield than the potential one. Suppose the new technology enable them to achieve more yield with the same water usage, then the farmers will find it more profitable to increase the water use.

With the optimal water use level $W(\xi)$, we will move back to the first stage, where the farmer choose the optimal investment on irrigation technology. Denote s as the subsidy on irrigation technology investment, the farm's objective function can be specified as:

$$\max_{\xi} \pi = \max_{\xi} PY(W(\xi),\xi) - C_w W(\xi) - (C(\xi) - s)\xi \tag{5}$$

The FOC for objective function (5) is:

$$\begin{aligned} \frac{\partial \pi}{\partial \xi} &= P\left(\frac{\partial Y}{\partial W}\frac{\partial W}{\partial \xi} + \frac{\partial Y}{\partial \xi}\right) - C_w \frac{\partial W}{\partial \xi} - (C(\xi) - s) - C'(\xi)\xi \\ &= P\frac{\partial Y}{\partial \xi} - (C(\xi) - s) - C'(\xi)\xi = 0 \end{aligned} \tag{6}$$

The second equality of (6) follows as a result of (2). As the subsidy s must be below the cost of technology investment, $C(\xi)$, thus from (6) we can readily obtain:

Result 3: After installation of the new irrigation technology, crop yield will increase under all circumstances.

Result 3 shows that crop yield will increase no matter water saving occurs or not. This shows that from the food security perspective, i.e., to meet the challenge of feeding an increasing population on the earth (Godfray et al. 2010), the new technology investment is always a good option. Combining Results 2 and 3, we know that if the water pumping cost is low, then both water saving and higher crop yield can be achieved at the same time with the installation of improved irrigation technology.

Next, we will investigate the effect of subsidy on irrigation technology investment. With a total differentiation w.r.t. s on Equation (6) and some further manipulations we can obtain:

$$\frac{\partial \xi}{\partial s} = \frac{-1}{\left[P\left(\frac{\partial^2 Y}{\partial \xi^2} + \frac{\partial^2 Y}{\partial \xi \partial w} \frac{\partial w}{\partial \xi} \right) - \left(2C'(\xi) + C''(\xi)\xi \right) \right]} > 0 \tag{7}$$

Equation (7) is signed as positive, supposing the second order sufficient condition (SOSC) for (5) holds, which is:

$$P\left(\frac{\partial^2 Y}{\partial \xi^2} + \frac{\partial^2 Y}{\partial \xi \partial w} \frac{\partial w}{\partial \xi} \right) - \left(2C'(\xi) + C''(\xi)\xi \right) < 0 \tag{8}$$

Equation (7) shows that if a higher subsidy is provided, then more investment on irrigation technology will be made, which leads to a higher irrigation efficiency. However, based Result 2, we know higher irrigation efficiency may not translate into water saving. Particularly, in areas where the pumping cost is high, government subsidy may not achieve much water conservation effect as it is intended. Among possible scenarios, lower water cost makes water saving more likely.

It is worth noting that using a different theoretical model coupled with some empirical analysis, Caswell and Zilberman (1986) also found drip and sprinkler technologies help save water in many cases except when water prices are high. In most cases, high pumping cost is due to heavy use of groundwater in the past, which lowered the satiation thickness and increased pumping lift. Therefore for the water saving to occur, the switching to higher efficiency technology should occur in a preventative stage, rather than in a stage where water shortage already poses a serious problem.

2.1.2. Increase in Water Cost

An increase in water cost can be caused by different factors such as a varied pumping lift across space, changing energy price over time (Hendricks and Peterson, 2012), or a tax on water use. In this subsection we will study the effect of an increased water cost on water usage. As the decision on whether or not to choose the more advanced irrigation technology is inevitably affected by the water cost, we will also analyze its effect on new technology investment decision as well. Overall water cost affect water use in two ways: one is the direct effect on water use, the other is the indirect effect on water use from the potential adoption of new irrigation technology.

Following the method in previous subsection, we will first solve the second-stage problem of deciding the optimal water use change when facing an increase in unit water cost, given the irrigation technology fixed. Next, we can solve the first-stage problem of determining the optimal irrigation technology. Re-write Equation (2) and express ξ as a function of C_w and take the total differentiation w.r.t. C_w generates:

$$P\left(\frac{\partial^2 Y}{\partial W^2}\frac{\partial W}{\partial C_w}+\frac{\partial^2 Y}{\partial W^2}\frac{\partial W}{\partial \xi}\frac{\partial \xi}{\partial C_w}+\frac{\partial^2 Y}{\partial W \partial \xi}\frac{\partial \xi}{\partial C_w}\right)-1=0 \tag{10}$$

By substituting (4) into (10), we obtain:

$$\frac{\partial W}{\partial C_w} = \frac{1}{P\dfrac{\partial^2 Y}{\partial W^2}} < 0 \qquad (11)$$

Similar to Huffaker and Whittlesey (2003), equation (11) shows that the combined effects, which includes direct effect and indirect effect, of water cost increase on water use is always negative, regardless of new technology adoption decisions. Next we will investigate the first-stage optimality problem, and obtain the effect of increased water price on irrigation technology investment. We can re-write Equation (6), characterizing the irrigation efficiency as dependent on unit water cost:

$$\frac{\partial \pi}{\partial \xi} = P\frac{\partial Y(W(\xi(C_w),C_w),\xi(C_w))}{\partial \xi} - C(\xi(C_w)) - C'(\xi(C_w))\xi(C_w) = 0$$

(12)

Taking a total differentiation w.r.t. C_w on equation (12), we have

$$P\left[\frac{\partial^2 Y}{\partial \xi \partial W}\left(\frac{\partial W}{\partial C_w} + \frac{\partial W}{\partial \xi}\frac{\partial \xi}{\partial C_w}\right) + \frac{\partial^2 Y}{\partial \xi^2}\frac{\partial \xi}{\partial C_w}\right] - \left(2C'(\xi) + C''(\xi)\xi\right)\frac{\partial \xi}{\partial C_w} = 0 \qquad (13)$$

By SOSC as specified in (8) and (11) we can further obtain:

$$\frac{\partial \xi}{\partial C_w} = -\frac{\dfrac{\partial^2 Y}{\partial \xi \partial W}\dfrac{\partial W}{\partial C_w}}{\dfrac{\partial^2 Y}{\partial \xi \partial W}\dfrac{\partial W}{\partial \xi} + \dfrac{\partial^2 Y}{\partial \xi^2} - \left(2C'(\xi) + C''(\xi)\xi\right)} \overset{\text{sign}}{=} -\frac{\partial^2 Y}{\partial \xi \partial W} \qquad (14)$$

From our previous illustration in Figure 1, we know that on one hand, when the water pumping cost is below $\overline{C_w}$, we have $\frac{\partial^2 Y}{\partial W \partial \xi} \leq 0$, or $\frac{\partial \xi}{\partial C_w} \geq 0$. This means before the pumping cost reaches a certain threshold level, farmers are more likely to adopt the more efficient irrigation technology as pumping cost increases. Figure 2 describes the direct effect of increasing water cost on water use, which is negative, as reflected by the blue arrow. An increase in water cost gives farmers an incentive to adopt the new irrigation technology. The indirect effect from the potential adoption of new irrigation technology, which in this case promotes water saving, is reflected by the red arrow. Overall effect is represented by the green arrow, showing that an increase in water cost causes water saving at the intensive margin.

On the other hand, when the water cost is above $\overline{C_w}$, we know $\frac{\partial \xi}{\partial C_w} < 0$. Under this situation farmers are less likely to adopt the more efficient irrigation technology as pumping cost further increases. Instead they will just maintain the current technology and use less water as a result of the price effect. In the extreme case, we know no farmer will install the new technology, and the best choice is to switch to dryland farming when the economic life of the aquifer ends. We can summarize our finding in Result 4:

Result 4: If the water pumping cost is below (above) threshold $\overline{C_w}$, then an increase in water cost will give farmers more (less) incentive to adopt the advanced technology. Whatever the pumping cost is, water saving is expected as a result of an increased water cost.

Result 4 implies that farmers located in areas with a high pumping cost are likely to use less water than those located in areas with low pumping cost. Given the same depth to water, farmers facing a lower energy cost are likely to extract more water. Using the farm level groundwater pumping data in Kansas, Pfeiffer and Lin (2014b) quantified the elasticity of water extraction to energy price as -0.26. Before the threshold water table is reached, farmers facing a high pumping cost are more likely to adopt the new technology. Similar result is also found by Caswell and Zilberman (1986), who concluded that advanced irrigation technology is more likely to be used in locations with deep wells.

Table 1 summarizes the effects of water cost increase vs. the irrigation technology subsidy. We can see that from the water saving perspective, cost increase is more effective than the technology subsidy in all scenarios. In case water pumping cost is low, then water cost increase achieves water saving through both direct effect and the indirect effect, while the technology subsidy only has the indirect effect. When the pumping cost is relatively high, then cost increase saves water through the direct effect only, while the technology subsidy will give farmer incentives to consume more water through the indirect effect. Similar to our finding, Huffaker and Whittlesey (2003) also favored water tax, rather than irrigation technology subsidy.

On the effectiveness of an increase in water cost, a caveat for our finding in Table 1 is that we have assumed the well pumping capacity is not a limiting factor for water use, at the given water cost. In reality, due to the declining groundwater level, the well pumping capacity is likely pose a water use constraint. In case water use is constrained by an upper bound, say W_c, then the FOC for the constrained objective function (1) will be:

$$\frac{\partial \pi}{\partial W} = P\frac{\partial Y}{\partial W}(W,\xi) - C_w \geq 0; \quad W \leq W_c \tag{2'}$$

The water use constraint in (2') will be binding as long as $C_w < PY_w(W_c,\xi)$. Suppose after the cost increase water cost is still no greater than $PY_w(W_c,\xi)$, then the water use will remain at W_c

before and after the price change. This explains the water demand inelasticity phenomenon, or that the farmers are less responsive to the water cost, especially when the increase is only by a small margin (Johnson et al., 2009; Huang et al., 2010; Watts, Atwood and Beattie, 2014). In situations where irrigation is restricted by the well pumping capacity, most often water price has to increase by a large margin to achieve the desired water saving amount, which greatly decreases farmer's profit. Therefore in areas where well pumping capacity poses a constraint, price increase by a small margin is generally ineffective. A dramatic increase, though very likely effective in curtailing water use, is likely to be met with harsh resistance. Feinerman and Knapp (1983) and Shi et al. (2014) suggested that farmers are more like to gain from water quotas, rather than the water tax. However, prevailing water law in Kansas and Texas guarantee farmers with the water right to use their water underlying their farm unlimitedly, a water use quota trying to limit water right might be difficult to implement as it dampens the short-run profit of farmers. Therefore in the next subsection we will discuss another policy alternative that compensates the farmers for water saved.

2.1.3. Price Subsidy for Water Saved

Compared to water price increase, price subsidy for saved water will not reduce farmer's income and thus can be more readily implemented. Suppose the optimal level of water use is W^*, then to give farmers incentive to use $W^R < W^*$ units of water, the government can set up a unit subsidy for the water saved. This subsection provides a study on the determinants of this subsidy.

Suppose the farmer uses only W^R amounts of water, then the total value product of the unused amount of water, $W^* - W^R$, can be calculated as $P\int_{W^R}^{W^*} \frac{\partial Y(W,\xi)}{\partial W}$. Therefore the foregone profit from saving $W^* - W^R$ units of water is $P\int_{W^R}^{W^*} \frac{\partial Y(W,\xi)}{\partial W} - (W^* - W^R)C_w$. To compensate the farmer for this loss, the unit price that government need to pay is thus:

$$s = \frac{P\int_{W^R}^{W^*} \partial Y(W,\xi)/\partial W}{W^* - W^R} - C_w \tag{15}$$

We know the subsidy defined in equation (15) is positive as $P\frac{\partial Y(W,\xi)}{\partial W}$ is decreasing in W and $P\frac{\partial Y(W^*,\xi)}{\partial W} = C_w$. From (15) we are ready to obtain the following result:

Result 5: 1) Given the same amount of subsidy, more water saving occurs for farmers with higher pumping cost, lower crop productivity and lower crop price; 2) given the crop price and pumping cost of water, higher subsidy for saved water provides the farmers with incentives to save more water; and 3) with higher crop price or lower pumping cost, to provide farmers incentives government needs to pay higher subsidy to save the same amount of water.

Note that in the extreme water saving case, W^R equates 0. The problem is essentially the government water right buyout program, in which government provides farmers compensation to convert their irrigated land to dryland. Suppose government offers a fixed amount of compensation for the buyout program, item 1) of Result 5 implies that only farmers with higher pumping cost or lower crop productivity have the most incentive to enroll. This is consistent with the observation by Pfeiffer and Lin (2009), that farmers often enroll their least productive land in the land retirement programs. From item 2) of Result 5, we can infer that more acres of land will be enrolled in the program when the fixed compensation rate towards dryland conversion is set higher. Based on item 3) of result 5, we know that a more cost efficient way, however, is to provide different compensation rate based on some ready-to-identify characteristics of the enrollment land such as depth to groundwater, previous record on irrigation use and crop productivity.

2.2. Multiple-Crop Scenario

Now we will expand our crop choices and assume that the farmer can grow a combination of two crops. For crop $i \in \{1, 2\}$, suppose the maximum crop yields are Y_i^m which is achievable at ET rates of E_i^m. These two crops have different satiation ET levels, or in other words, one crop is more water intensive than the other. In Southern Great Plain area, one might easily think of corn and cotton as examples. Suppose the same irrigation technology is applicable to both crops on the farm. Thus the crop yield function is modeled as $Y_i = Y_i(W_i, \xi)$, which is an increasing and concave function w.r.t. the water application level and the irrigation efficiency.

Assume ℓ_i percent of the land allocated to grow crop i with $\sum_i \ell_i \le 1$. Of the two crops, we assume that crop 1 is more water intensive than crop 2. Specifically, suppose the following assumptions hold as summarized below:

Assumption 1: Assume that the following conditions hold: 1) $E_1^m > E_2^m$; 2) $P_1 Y_1^m > P_2 Y_2^m$; 3) $P_1 \frac{\partial Y_1}{\partial W_1}(0,\xi) \le P_2 \frac{\partial Y_2}{\partial W_2}(0,\xi)$ and 4) $P_1 \frac{\partial^2 Y_1}{\partial W_1 \partial \xi}(0,\xi) \le P_2 \frac{\partial^2 Y_2}{\partial W_2 \partial \xi}(0,\xi)$ and $P_1 \frac{\partial^2 Y_1}{\partial W_1 \partial \xi}(W,\xi) - P_2 \frac{\partial^2 Y_2}{\partial W_2 \partial \xi}(W,\xi)$ is an increasing function in W.

Condition 1 of Assumption 1 implies that crop 1 has a higher satiation ET level than crop 2; while condition 2 means that at their satiation ET rates, crop 1 generates higher revenue than crop 2, otherwise the farmer will simply not plant crop 1 given its higher satiation ET level; condition 3 holds because as a water-conservation crop, crop 2 is more drought tolerant. Therefore under dryland production and extremely low irrigation levels, the MVP of water on crop 2 is no lower than that on crop 1; condition 4) means under dryland production and extremely low irrigation levels, due to its drought tolerant nature crop 2 is more responsive to the irrigation efficiency increase. However, as water use increases, the MVP of water on crop 1 increases more (or decreases less in low pumping cost) than that on crop 2 in response to a unit level of irrigation efficiency increase .

Similar to the single-crop scenario we will solve the farmer's water management problem using the backward induction approach. We will investigate whether improved irrigation efficiency gives farmer an incentive to save water on both intensive and extensive margins. Suppose the irrigation technology is chosen as ξ in the first stage, the farmer will choose the optimal level of water usage $W_i(\xi)$ and the optimal land allocation $l_i(\xi)$ in the second stage to maximize the overall profit:

$$\begin{aligned} &\max_{W_i,l_i} \pi = \max_{W_i,l_i} \sum_{i=1}^{2} l_i P_i Y_i(W_i,\xi) - C_w \sum_{i=1}^{2} l_i W_i \\ &s.t. \qquad \sum_i l_i \le 1; \quad l_i \ge 0 \ . \qquad (i=1,2). \end{aligned} \tag{16}$$

The Lagrangian function can be written as:

$$L = \sum_{i=1}^{2} l_i P_i Y_i(W_i,\xi) - C_w \sum_{i=1}^{2} l_i W_i + \lambda(\sum_i l_i - 1) + \sum_i \gamma_i l_i \tag{17}$$

For $i \in \{1, 2\}$, the FOCs for Lagrangian function (17) are:

$$l_i P_i \partial Y_i / \partial W_i (W_i(\xi), \xi) - l_i C_w = 0 \qquad (18)$$

$$P_i Y_i(W_i, \xi) - C_w W_i + \lambda + \gamma_i \leq 0 \ ; \ l_i \geq 0 \ ; \ l_i (P_i Y_i(W_i, \xi) - C_w W_i + \lambda + \gamma_i) = 0 \qquad (19)$$

$$\sum_i l_i - 1 \leq 0 \ ; \lambda \geq 0 \ ; \ \lambda(\sum_i l_i - 1) = 0 \qquad (20)$$

$$l_i \geq 0 \ ; \gamma_i \leq 0 \ ; \ l_i \gamma_i = 0 \qquad (21)$$

2.2.1. Interior Solutions

In this subsection we will consider the interior solution only, which means for $i = 1, 2$, $l_i \neq 0$. This implies from (21) that $\gamma_i = 0$. From FOCs (18) and (19) we can further derive the following set of conditions:

$$\begin{aligned} &P_i \frac{\partial Y_i}{\partial W_i}(W_i(\xi), \xi) - C_w = 0 \ ; && i \in \{1, 2\} \\ &P_i Y_i(W_i, \xi) - C_w W_i = P_j Y_j(W_j, \xi) - C_w W_j \ ; && i, j \in \{1, 2\} \end{aligned} \qquad (22)$$

From Equation set (22) we can see that if it is optimal to grow two crops together, then two criteria must be satisfied simultaneously: 1) for each crop the MVP of water equates its marginal cost; and 2) on a per area basis, optimized profits are equal for two crops. This is because if one crop could generate a higher profit than the other, then farmers will use all the land to plant this crop only. In reality, however, multi-crop scenario reduces the uncertainty of crop prices and production risks such as pest infestation and is thus always preferred to the single-crop scenario (Rosegrant, Schleyer and Yadav, 1995). For the sake of simplicity, we will account for these factors in our model.

To see how the adoption of new irrigation technology will alter the water demand for the two crops we will carry out comparative statics analysis w.r.t. ξ. A total differentiation w.r.t. ξ on the Equation set (22) generates:

$$\begin{aligned} &\frac{\partial^2 Y_i}{\partial W_i^2}\frac{\partial W_i}{\partial \xi}+\frac{\partial^2 Y_i}{\partial W_i \partial \xi}=0 && i\in\{1,2\} \\ &P_i\frac{\partial Y_i}{\partial \xi}=P_j\frac{\partial Y_j}{\partial \xi} && i,j\in\{1,2\} \end{aligned} \qquad (23)$$

From Equation set (23) we can further derive the following conditions:

$$\frac{\partial W_i}{\partial \xi}=-\frac{\dfrac{\partial^2 Y_i}{\partial W_i \partial \xi}}{\dfrac{\partial^2 Y_i}{\partial W_i^2}}; \qquad \frac{\dfrac{\partial Y_i}{\partial \xi}}{\dfrac{\partial Y_j}{\partial \xi}}=\frac{P_j}{P_i} \qquad i,j\in\{1,2\}, i\neq j. \qquad (24)$$

Suppose interior solution is still optimal after irrigation efficiency improvement, then based on the last equation of (22), the farmer can allocate the land with no proportion restriction. In addition, as the first equation of (24) resembles Equation (4), therefore the rule of water saving in the single-crop scenario, as summarized in Result 2, still applies under the multi-crop case. It is likely that the threshold water pumping cost $\overline{C_w}$, as defined in Result 1, differs across varied crops. Therefore for certain ranges of pumping cost, the installation of new irrigation technology may increase the optimal water demand for one crop, while decrease that for another. Based on Result 3 and the last equation of (24), we can see the crop yield for each crop will increase after the efficiency improvement, regardless of its water use change.

2.2.2. Corner Solutions

In contrast to the interior solutions, we can also identify conditions under which corner solutions are optimal, as shown in Result 6:

Result 6: Corner solutions exist under either of the two cases: 1) the maximum MVP of water on one crop is less than the water pumping cost, or $P_i \frac{\partial Y_i}{\partial W_i}(0,\xi) < C_w$; and 2) the optimal profit of one crop is less than that of the other, or $P_i Y_i(W_i,\xi) - C_w W_i < P_j Y_j(W_j,\xi) - C_w W_j$.

Based on condition 1) of Result 6, hereafter we assume that the water pumping cost is below $C_w^0 \equiv \max_i \left\{ P_i \partial Y_i / \partial W_i(0,\xi) \right\}$. If this is not the case, and the cost of irrigation is higher than the maximum MVP of water on both crops, then the optimal irrigation level is zero and dryland production will be chosen. Suppose the MVP of water is increased by some exogenous factors such as improved irrigation technology, then some farmers may find it profitable to switch from dryland to irrigation production. That explains the empirical observation of an expansion of irrigated land following the new technology adoption in Kansas (Pfeiffer and Lin, 2014a). In addition to the choice of irrigation area, next we will demonstrate that the farmer's decision on crop pattern is also contingent on the water cost.

Result 7: Suppose Assumption 1 holds. There exist two threshold water use levels, $W_T(\xi)$ and $\overline{W}(\xi)$, defined implicitly in $P_1 \partial Y_1 / \partial W_1(W_T(\xi),\xi) = P_2 \partial Y_2 / \partial W_2(W_T(\xi),\xi)$ and $P_1 Y_1(\overline{W}(\xi),\xi) = P_2 Y_2(\overline{W}(\xi),\xi)$. Define $C_w^H(\xi) \equiv P_1 \partial Y_1 / \partial W_1(W_T(\xi),\xi)$ and $C_w^L(\xi) \equiv P_1 \partial Y_1 / \partial W_1(\overline{W}(\xi),\xi)$. If the water cost is higher than $C_w^H(\xi)$, then only crop 2 will be produced. If the water cost is lower than $C_w^L(\xi)$, then only crop 1 will be produced.

A graphical illustration of Result 7 is provided in Figure 3 (a). Suppose the water cost is higher than $C_w^H(\xi)$, then the corresponding profit maximizing water usages for both crops are lower than $W_T(\xi)$. In this case $P_1\partial Y_1/\partial W_1(W,\xi) \le P_2\partial Y_2/\partial W_2(W,\xi)$, which implies $W_1^* < W_2^* < W_T(\xi)$[5]. Therefore the profit-maximizing water uses for both crops lie in the green shaded area, and only crop 2 will be produced as it generates a high profit. On the contrary, if the water cost is lower than $C_w^L(\xi)$, then $W_1^* > W_2^* > \overline{W}(\xi)$. Therefore the profit-maximizing water usages for both crops lie in the red shaded area and only crop 1 will be produced.

2.2.3. Improved Irrigation Efficiency

In this subsection we will investigate the water saving potential from the improved irrigation efficiency, when multiple crop choices are available, with a focus on the change in crop patterns. Based on Result 7 we have the following result:

Result 8: Both threshold water use levels, $W_T(\xi)$ and $\overline{W}(\xi)$, will decrease with higher irrigation efficiency ξ.

When there are only two technologies available, according to Result 8 we know $W_T(\xi_H) < W_T(\xi_L)$ and $\overline{W}(\xi_H) < \overline{W}(\xi_L)$. Figure 3(a) and 3(b) illustrates this point, with the former depicting water production functions for the two crops under the old technology, while the latter shows the corresponding functions under new irrigation technology. We can readily see that compared to Figure 3(a), the green area (crop 2 only area) in Figure 3 (b) shrinks while red area

[5] Note that W_1^*, W_2^* stands for the profit maximizing water use for each crop, which may not be the optimal water use when two crops are considered. For example, if the maximized profit of crop 1 is less than that of crop 2, then the optimal water use for crop 1 is specified as zero.

(crop 1 only area) expands. This means farmers tend to have the incentive to make the shift from water-conservative crop to water-intensive crop upon irrigation technology improvement. More specifically, upon irrigation technology improvement, based on Results 7 and 8 we will describe crop pattern changes at different groundwater pumping cost scenarios as summarized in Table 2.

Among the five scenarios listed in Table 2, for scenarios 1 and 5 the same crop type will be maintained before and after the irrigation efficiency improvement, therefore we essentially have the single-crop case as previously discussed. Based on Result 2 we know that for Scenario 1 water saving is possible at the low water cost, while water saving is unlikely to occur for Scenario 5 due to the high pumping cost. For Scenario 2, 3 and 4, water use will increase at the extensive margin as the proportion of water-intensive crop will increase after the irrigation efficiency increase. Overall, except for Scenario 1 where the water pumping cost is low, water use generally increase in the rest scenarios, either at the intensive margin, or at the extensive margin, or both.

Therefore, if the farmers are facing a high pumping cost, or low groundwater table, then a subsidy to increase irrigation efficiency is not likely to achieve the water saving effect as desired by the policy makers. Conversion to more water-intensive crops and higher water use on existing crops are consequences of the rational decision making.

2.2.4. Increase in Water Cost

Suppose optimal water use is not restrained by well pumping capacity, an increase in unit water cost will decrease the profit maximizing water usage for both crops due to the decreasing level of MVPs of water at higher water use amount. Using Figure 3(a) as an illustration, upon an increase in unit water cost, we are moving to the left along the MVP curves from the red area to the green area. Therefore based on Result 7 water saving at extensive margin from switching from crop 1 to crop 2 is likely to occur with the high water pumping cost.

Therefore in regions with deep wells the farmers are likely to grow water-conservation crop due to high water pumping cost, while water-intensive crop is more likely to be produced in regions where the water pumping cost is low. Similarly, a unit water tax or an increase in energy price increase can also cause farmers to switch from water-intensive to water-conservative crop.

2.2.5. Subsidy on the Price of Water-Conservation Crop

Now we will investigate the effect of another policy alternative, i.e., subsidy on the price of water-conservation crop. It is easy to show that a tax on the price of water-intensive crop has an equivalent effect, since it is the price ratio between two crops that matters. As a subsidy is always easier to implement than a tax, we will only study the effect of the subsidy for water-conservation crop. Similar to Result 8, the following result can be proven on water usage thresholds.

Result 9: There exist two threshold water usage levels, $W_T(s)$, $\overline{W}(s)$, defined implicitly in $P_1 \partial Y_1 / \partial W_1(W_T(s), \xi) = P_2 \partial Y_2 / \partial W_2(W_T(s), \xi)$ and $P_1 Y_1(\overline{W}(s), \xi) = (P_2 + s) Y_2(\overline{W}(s), \xi)$. If the price subsidy to water-conservative crop, s, increases, so does $W_T(s)$ and $\overline{W}(s)$.

The implication of Result 9 is obvious with a comparison between Figure 3(a) and 3(c), as the latter has noticeable expanded green area and decreased red area than the former. Therefore with a subsidy to water-conservative crop, farmers will likely find it more profitable to grow crop 2 or a higher proportion of crop 2. Given the farmers in different locations are facing different pumping costs, as the subsidy increases, more farmers will make the switch from crop 1 to crop 2.

While under a new technology subsidy it is likely for farmers to shift from the water-conservative to the water-intensive crop, the opposite happens under the price subsidy for water-conservative crop and water saving will occur from both the intensive margin and extensive margin. Therefore from the water saving perspective, the price subsidy for water-conservative crop is always more effective than the irrigation technology subsidy.

3. Discussion

In contrast to the government, whose goal is long run water conservation, the farmers regard it as a priority is to increase their immediate profit. In pursuit of such short-term goal, farmers may take advantage of the government funded program to gain additional profit. Due to the different objectives of the government and individual farmers, a well-intentioned policy alternative often falls short of its purpose. Therefore a successful incentive based program is to align the farmer's short-run objective to that of the social planner long-run objective.

One of our results suggests that as a result of an efficiency increase, farmers with high water pumping cost will increase irrigation water demand on the existing crop, and replace the water-conservative crops with water-intensive crops. This finding coincides with the empirical finding of Pfeiffer and Lin (2014a), who showed western Kansas farmers increased their water use from both the intensive margin and extensive margin, after conversion from traditional center pivot irrigation systems to higher efficiency dropped-nozzle center pivot systems from 1995 to 2005. As Pfeiffer and Lin (2014a) pointed out, the farmers in studied area were extremely conservation minded and the conversion was driven by reduction in well capacity as a result of the falling water table. It can be inferred that these farmers in studied area incur a water pumping cost above our threshold cost specified in Result 2.

The increase in water use due to efficiency improvement is a special case of the “rebound effect”, first brought out by Jevons (1865), indicating enhanced technology efficiency does not necessarily reduce the natural resource consumption. In our case, the rebound effect in irrigation water usage is a rational economic reaction towards a very limited resource. As a technology improvement subsidy is very effective in increasing crop production, the farmers are likely to gain additional profit from such conversion. However, the water depletion problem could become more serious. It is clear that the efficiency-enhancing technology has more benefits to farmers than to the society. Thus the cost of new technology adoption should be borne largely by the farmers in this situation.

Our results also demonstrate that advanced irrigation technology in regions with low pumping cost can effectively lower the use of ground water. Usually, farmers in those regions have much less intention to increase their irrigation efficiency (Caswell and Zilberman, 1986). In addition, with low pumping water cost, farmers generally use more irrigation water per acre when compared to their peers facing the high pumping cost. As Wheeler (2008) point out, society are likely to benefit more from water conservation policies targeting those heavy water use areas. Therefore, subsidy for more efficient irrigation technology is more justified in areas with low groundwater depth.

To achieve the water saving goals in regions with high pumping cost, rather than providing subsidy for the new technology installation or charging a unit water tax, unit subsidy for saved water and subsidy for water-conservation crop are more promising to achieve water-saving, as it directly rewards farmers for actual water saved. Water right retirement program, or water buyout program is one such example that provides a compensation on a land size basis for farmers willing to retire their water right. However, as our result shows, a fixed compensation rate tend to attract the land with low productivity and high water cost. In line with our finding, Pfeiffer and Lin (2009) also pointed out that enrollment of the non-irrigated land plot in such programs helps little to achieve water conservation. Thus, to be more cost effective, government payment offer should be contingent on land characteristics. For example, the government may develop relevant criteria and categorize land into several categories, such as excellent, good and poor. Different levels of compensations can be offered contingent on the water saving potential of a specific land to be retired.

4. Conclusion

Various water conservation policy alternatives have been implemented or promoted to extend the economic life of Ogallala Aquifer in the Southern Great Plains where rapid groundwater level decline is an ongoing concern. As Rule of Capture remaining the primary law in governing groundwater in states such as Kansas and Texas, incentive-based water conservation programs are more popular with farmers. However, as Pfeiffer and Lin (2009) pointed out, voluntary and incentive-based water conservation programs may have “unintended or even perverse consequences”. In this regard, very few attempts have been made to analyze the effectiveness of different policy alternatives in incentivizing individual farmer to actually save water. In addition, the effectiveness of policy alternatives may differ based on the regional characteristics such as groundwater depth, satiation thickness and feasible crop patterns. Yet conceptual models on farmer incentive studies rarely take these factors into account.

Our paper filled in those gaps by studying farmer's incentive-driven responses to the following policy tools, including 1) irrigation technology subsidy, 2) increased water cost, 3) unit subsidies for water saving; and 4) subsidies on water-conservative crop. We found in regions with high pumping cost, no water saving will occur after converting to a more efficient technology. Instead, farmers take advantage of the new technology to pursue increased profit. While the technology subsidy can be effective in the preventative stage, or before water table declines too much, it is often unjustified when water depletion is already a serious problem. Similarly, an increase in water cost may serve its purpose if well pumping capacity is not a constraint. However, if well pumping capacity is limited due to falling groundwater level, the cost increase may not be practical as water usage will not respond to the small price increase. To achieve the required water saving goal it often takes a large price increase, which is detrimental to the farmers' profit and is likely to be met with resistance on implementation.

We find policy alternatives such as subsidy for unit water saved and price subsidy for water conservative crop, are likely effective in achieving water conservation even in case of high pumping cost. Therefore in areas where groundwater is already a constraint, the direct reward for actual water saved or planting water saving crops serves the conservation purpose better. Compared to the subsidy of new technology, subsidy for water saved discourages the farmer from using the saved water to gain additional profit, while subsidy for water-conservative crop reduces the irrigation demand from the extensive margin.

Beyond the policy implications, our paper also poses some hypotheses to be further tested by empirical studies. For example, among the farmers that adopt more efficient technologies, is there any relationship between water use adjustment and pumping cost? Previous to the enrollment, is the average irrigation amount of the land enrolled in water buyout program comparable to that of the land outside of the program? Future studies may also study the relationship between water pumping cost, crop price and crop patterns, to identify the proper price subsidy to more water-conservative crops to achieve the water conservation goal. Rather than the social planner's approach, theoretical modeling from the farmer's standpoint as well as empirical studies based on farm level data in different regions could provide policy makers with more detailed information on the extent of water saving towards varied water conservation policy tools. After all, it is the farmers who make the water-conservation decisions.

Acknowledgements

Funding support from USDA Agricultural Research Service Initiative-Ogallala Aquifer Program (FY2014-2015) is gratefully acknowledged.

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Supplementary Appendix

Proof of Result 1:

Define $f(W)=\frac{\partial Y(W,\xi^{H})}{\partial W}-\frac{\partial Y(W,\xi^{L})}{\partial W}$. As crop yield function is twice differentiable w.r.t. W, we can see $f(W)$ is continuous. In addition, $f(0)>0$ and $f(W_H^m)<0$, then by Intermediate Value Theorem (IVT), there must exists $\overline{W}\in(0,W_H^m)$ such that $f(\overline{W})=0$. □

Proof of Result 6:

Criterion 1): It is easy to show that if $P_1\frac{\partial Y_1}{\partial W_1}(0,\xi)<C_w$, then by (18) we know that $l_1=0$.

Criterion 2): Suppose at the optimal water usage level we have $P_1Y_1(W_1,\xi)-C_wW_1$ $<P_2Y_2(W_2,\xi)-C_wW_2$, which means crop two is more profitable, then $l_1=0$.

Suppose this is not the case, and for $i=1,2$, $l_i>0$. Then by (21) we know $\gamma_i=0$;

and by (19) we have $P_iY_i(W_i,\xi)-C_wW_i+\lambda+\gamma_i=0$, with these two equations we obtain $P_1Y_1(W_1,\xi)-C_wW_1=P_2Y_2(W_2,\xi)-C_wW_2$. A contradiction. □

Proof of Result 7:

First we will prove that if the profit-maximizing water use on Crop 1, W_1^*, is below $W_T(\xi)$, then only crop 2 will be produced.

If $W_1^*<W_T(\xi)$, then it implies that for crop 2 profit-maximizing water use level is higher, or $W_2^*>W_1^*$, as $\frac{\partial Y_2}{\partial W_2}(W_1^*,\xi)>\frac{\partial Y_1}{\partial W_1}(W_1^*,\xi)$. We can also easily show that $W_2^*<W_T(\xi)$, because if otherwise, then $\frac{\partial Y_2}{\partial W_2}(W_2^*,\xi)<\frac{\partial Y_2}{\partial W_2}(W_T(\xi),\xi)=\frac{\partial Y_1}{\partial W_1}(W_T(\xi),\xi)<\frac{\partial Y_1}{\partial W_1}(W_1^*,\xi)$.

Based on $W_1^*<W_2^*<W_T(\xi)$, we have:

$$PY_1(W_1^*,\xi) - C_w W_1^* < PY_2(W_1^*,\xi) - C_w W_1^* < PY_2(W_2^*,\xi) - C_w W_2^* \qquad \text{(A1)}$$

The first inequality in (A1) holds when we integrate over W on both sides of $\frac{\partial Y_1}{\partial W_1}(W,\xi) \le$ $\frac{\partial Y_2}{\partial W_2}(W,\xi)$ from 0 to W_1^*, which holds for every $W \le W_T(\xi)$. The second inequality in (A1) holds as W_2^* is the profit-maximizing water use level for crop 2.

From (A1) we know only crop 2 will be produced, according to corner solution criterion 2) in Result 6.

Next we will prove that if the profit-maximizing water use on crop 2, W_2^*, is above $\overline{W}(\xi)$, then only crop 1 will be produced.

For $W > W_T(\xi)$ we have $\frac{\partial Y_1}{\partial W_1}(W,\xi) > \frac{\partial Y_2}{\partial W_2}(W,\xi)$. As $W_2^* > \overline{W}(\xi) > W_T(\xi)$, it requires that crop 1's profit-maximizing water use level is higher, or $W_1^* > W_2^*$, such that the profit maximizing condition $\frac{\partial Y_1}{\partial W_1}(W_1^*,\xi) = \frac{\partial Y_2}{\partial W_2}(W_2^*,\xi)$ can be satisfied. In this case it can be inferred:

$$PY_1(W_1^*,\xi) - C_w W_1^* > PY_1(W_2^*,\xi) - C_w W_2^* > PY_2(W_2^*,\xi) - C_w W_2^* \qquad \text{(A2)}$$

The first inequality of (A2) holds as W_1^* is the profit-maximizing water use level for crop 1. The second inequality of (A2) holds as $PY_1(W,\xi) > PY_2(W,\xi)$ for $W > \overline{W}(\xi)$. Based on (A2) and Result 6 we know only crop 1 will be produced. □

Proof of Result 8:

Based on Result 7, we have:

$$P_1 \partial Y_1 / \partial W_1(W_T(\xi),\xi) = P_2 \partial Y_2 / \partial W_2(W_T(\xi),\xi) \qquad \text{(A3)}$$

A total derivation w.r.t. ξ on both sides of (A3) generates the following condition at $(W_T(\xi),\xi)$:

$$P_1\left(\frac{\partial^2 Y_1}{\partial W_1^2}\frac{\partial W_T(\xi)}{\partial \xi}+\frac{\partial^2 Y_1}{\partial W_1 \partial \xi}\right)=P_2\left(\frac{\partial^2 Y_2}{\partial W_2^{\ 2}}\frac{\partial W_T(\xi)}{\partial \xi}+\frac{\partial^2 Y_2}{\partial W_2 \partial \xi}\right) \tag{A4}$$

From (A4) we can solve that:

$$\frac{\partial W_T(\xi)}{\partial \xi}=\frac{P_2\frac{\partial^2 Y_2}{\partial W_2 \partial \xi}(W_T(\xi),\xi)-P_1\frac{\partial^2 Y_1}{\partial W_1 \partial \xi}(W_T(\xi),\xi)}{P_1\frac{\partial^2 Y_1}{\partial W_1^{\ 2}}(W_T(\xi),\xi)-P_2\frac{\partial^2 Y_2}{\partial W_2^{\ 2}}(W_T(\xi),\xi)} \tag{A5}$$

The denominator in (A5) is greater than 0, since by Assumption 1, conditions 2) and 3) we can infer that $P_1 \partial Y_1 / \partial W_1(W,\xi)-P_2 \partial Y_2 / \partial W_2(W,\xi)$ is increasing in W.

Next we will prove the sign of numerator of (A5) is negative. By the first equation of (22) and the definition of $W_T(\xi)$, we know $W_T(\xi)$ are the optimal water use for both crops under pumping cost $C_w^H(\xi)$. According to the last equation of (23) the following condition holds:

$$P_1\frac{\partial Y_1}{\partial \xi}(W_T(\xi),\xi)-P_2\frac{\partial Y_2}{\partial \xi}(W_T(\xi),\xi)=0 \tag{A6}$$

Furthermore, condition 4) of Assumption 1 shows that $P_1\frac{\partial^2 Y_1}{\partial W_1 \partial \xi}(0,\xi)-P_2\frac{\partial^2 Y_2}{\partial W_2 \partial \xi}(0,\xi)\le 0$.

Therefore we know there exists a $\underline{W} < W_T(\xi)$, and we have:

$$P_1\frac{\partial^2 Y_1}{\partial W_1 \partial \xi}(W,\xi)-P_2\frac{\partial^2 Y_2}{\partial W_2 \partial \xi}(W,\xi)>0,\ \forall W \ge \underline{W} \tag{A7}$$

Otherwise if we integrate over W on the left hand of (A7) from 0 to $W_T(\xi)$, we cannot obtain (A6). Therefore by (A5) we know $\frac{\partial W_T(\xi)}{\partial \xi}<0$.

Similarly, $\overline{W}(\xi)$ is implicitly defined in $P_1Y_1(\overline{W}(\xi),\xi) = P_2Y_2(\overline{W}(\xi),\xi)$. Taking a total derivation w.r.t. ξ on both sides generates the following condition at $(\overline{W}(\xi),\xi)$:

$$P_1\left(\frac{\partial Y_1}{\partial W_1}\frac{\partial \overline{W}(\xi)}{\partial \xi}+\frac{\partial Y_1}{\partial \xi}\right) = P_2\left(\frac{\partial Y_2}{\partial W_2}\frac{\partial \overline{W}(\xi)}{\partial \xi}+\frac{\partial Y_2}{\partial \xi}\right) \quad \text{(A8)}$$

From (A8) we can derive:

$$\frac{\partial \overline{W}(\xi)}{\partial \xi} = \frac{P_2\frac{\partial Y_2}{\partial \xi}(\overline{W}(\xi),\xi) - P_1\frac{\partial Y_1}{\partial \xi}(\overline{W}(\xi),\xi)}{P_1\frac{\partial Y_1}{\partial W_1}(\overline{W}(\xi),\xi) - P_2\frac{\partial Y_2}{\partial W_2}(\overline{W}(\xi),\xi)} \quad \text{(A9)}$$

The denominator in (A9) is greater than 0, since we know $\overline{W}(\xi) \geq W_T(\xi)$ and for $W \geq W_T(\xi)$, $P_1\frac{\partial Y_1}{\partial W_1}(W,\xi) - P_2\frac{\partial Y_2}{\partial W_2}(W,\xi) \geq 0$.

By an addition of (A6) and the integration of the left side of (A7) from $W_T(\xi)$ to $\underline{W}$, we know the numerator of (A9) is less than 0. Therefore $\frac{\partial \overline{W}(\xi)}{\partial \xi} < 0$. □

Proof of Result 9:

From condition 3) of Assumption 1 we can infer that:

$$P_1\partial Y_1 / \partial W_1(0,\xi) \leq (P_2+s)\partial Y_2 / \partial W_2(0,\xi) \quad \text{(A10)}$$

As $E_1^m > E_2^m$, we know that:

$$P_1\partial Y_1 / \partial W_1(E_2^m/\xi,\xi) \geq (P_2+s)\partial Y_2 / \partial W_2(E_2^m/\xi,\xi) \quad \text{(A11)}$$

Based on (A10) and (A11), by IVT we know a threshold level $W_T(s) \in [0, E_2^m/\xi]$ exists, such that:

$$P_1 \partial Y_1 / \partial W_1 (W_T(s), \xi) = (P_2 + s) \partial Y_2 / \partial W_2 (W_T(s), \xi) \tag{A12}$$

Also, by condition 2) of Assumption 1 we assume there exists a $\overline{W}(s)$, such that:

$$P_1 Y_1(\overline{W}(s), \xi) = (P_2 + s) Y_2(\overline{W}(s), \xi) \tag{A13}$$

First we will show that if the subsidy to crop 2, s, increases, then $W_T(s)$ defined implicitly in (A12) will increase.

Take a total derivative of (A12) w.r.t. s we can obtain:

$$P_1 \frac{\partial^2 Y_1}{\partial W_1{}^2}(W_T(s), \xi) \frac{\partial W_T(s)}{\partial s} = (P_2 + s) \frac{\partial^2 Y_2}{\partial W_2{}^2}(W_T(s), \xi) \frac{\partial W_T(s)}{\partial s} + \frac{\partial Y_2}{\partial W_2}(W_T(s), \xi) \tag{A14}$$

We can solve from (A14) that:

$$\frac{\partial W_T(s)}{\partial s} = \frac{\frac{\partial Y_2}{\partial W_2}(W_T(s), \xi)}{P_1 \frac{\partial^2 Y_1}{\partial W_1{}^2}(W_T(s), \xi) - (P_2 + s) \frac{\partial^2 Y_2}{\partial W_2{}^2}(W_T(s), \xi)} \tag{A15}$$

It is obvious that the numerator of (A15) is positive. From (A10), (A11) and (A12) we know that the denominator of (A15) is positive. Therefore $\frac{\partial W_T(s)}{\partial s} \geq 0$.

Next we can prove that $\overline{W}(s)$, defined implicitly in (A11), will increase. A total derivative on both sides of (A13) w.r.t. s generates:

$$P_1 \frac{\partial Y_1}{\partial W_1}(\overline{W}(s), \xi) \frac{\partial \overline{W}(s)}{\partial s} = (P_2 + s) \frac{\partial Y_2}{\partial W_2}(\overline{W}(s), \xi) \frac{\partial \overline{W}(s)}{\partial s} + Y_2(\overline{W}(s), \xi) \tag{A16}$$

Therefore:

$$\frac{\partial \overline{W}(s)}{\partial s} = \frac{Y_2(\overline{W}(s), \xi)}{P_1 \frac{\partial Y_1}{\partial W_1}(\overline{W}(s), \xi) - (P_2 + s) \frac{\partial Y_2}{\partial W_2}(\overline{W}(s), \xi)} \tag{A17}$$

Based on (A11), (A12) and $W_T(s) \le \overline{W}(s)$, we know the denominator of (A17) is positive.

Thus $\frac{\partial \overline{W}(s)}{\partial s} \ge 0$. □

Table 1: Impacts of different policy tools on irrigation technology and water use

Farm Characteristics	Low Pumping Lift		High Pumping Lift	
Policy tool	Technology Subsidy	Water Cost Increase	Technology Subsidy	Water Cost Increase
Irrigation Efficiency	Improved	Improved	Improved	No change
Water Use (OE)	Reduced	Reduced	Increased	Reduced
Water Use (DE)	N/A	Reduced	N/A	Reduced
Water Use (IDE)	Reduced	Reduced	Increased	No change

Note: DE means direct effect and IDE means indirect effect, and OE means overall effect, which is a combination of DE and IDE.

Table 2: Impacts of different policy tools on irrigation technology and water use

Scenario	**Water Cost**	**Low Efficiency**	$\Rightarrow$	**High Efficiency**
1	$(0, C_w^L(\xi_L)]$	Crop 1 only	$\Rightarrow$	Crop 1 only
2	$(C_w^L(\xi_L), C_w^L(\xi_H)]$	Mixture	$\Rightarrow$	Crop 1 only
3	$(C_w^L(\xi_H), C_w^H(\xi_L)]$	Mixture	$\Rightarrow$	Mixture
4	$(C_w^H(\xi_L), C_w^H(\xi_H)]$	Crop 2 only	$\Rightarrow$	Mixture
5	$(C_w^H(\xi_H), C_w^0]$	Crop 2 only	$\Rightarrow$	Crop 2 only

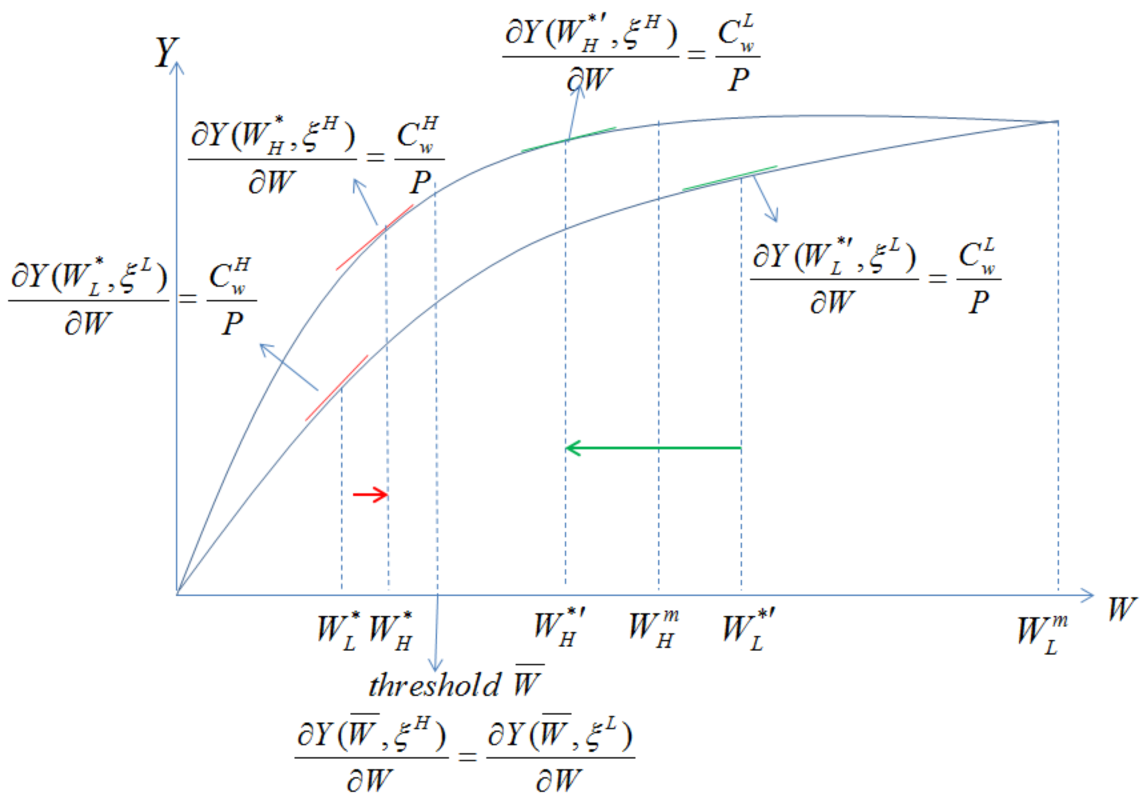

Figure 1: Illustration of optimal water usage change with crop yield function curves under two irrigation efficiency levels: two possible scenarios under different water costs.

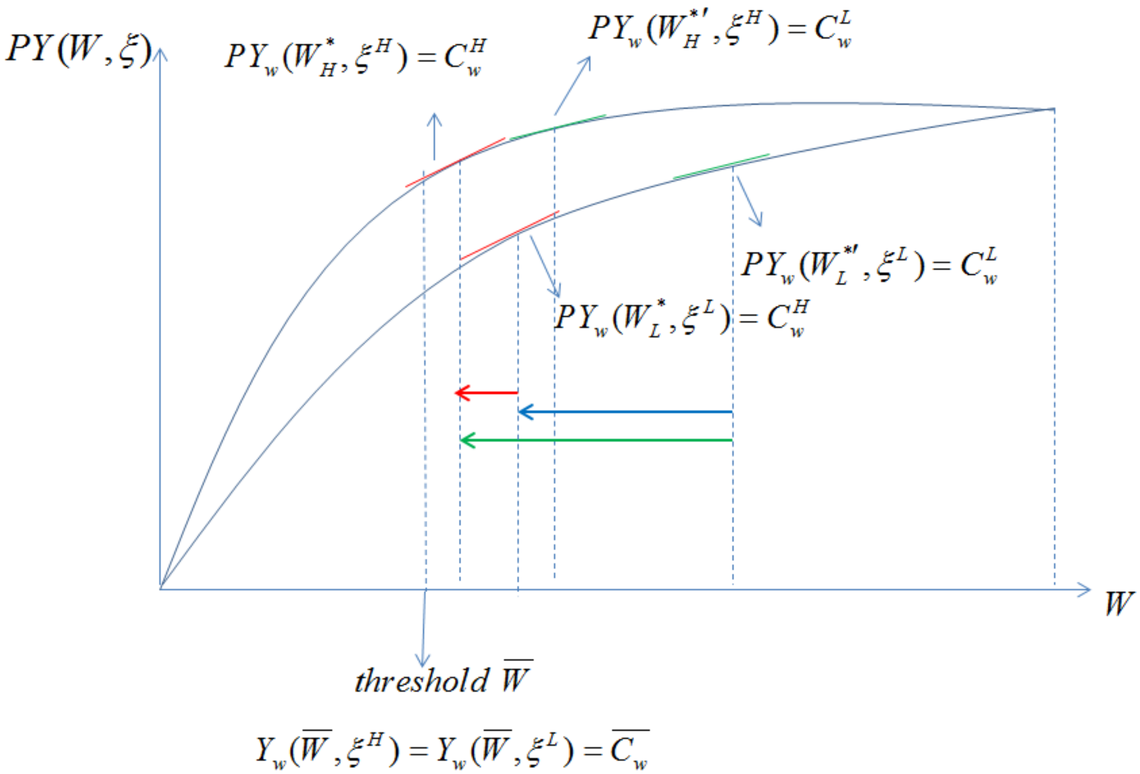

Figure 2: Illustration of effect of unit water tax on optimal water usage change.

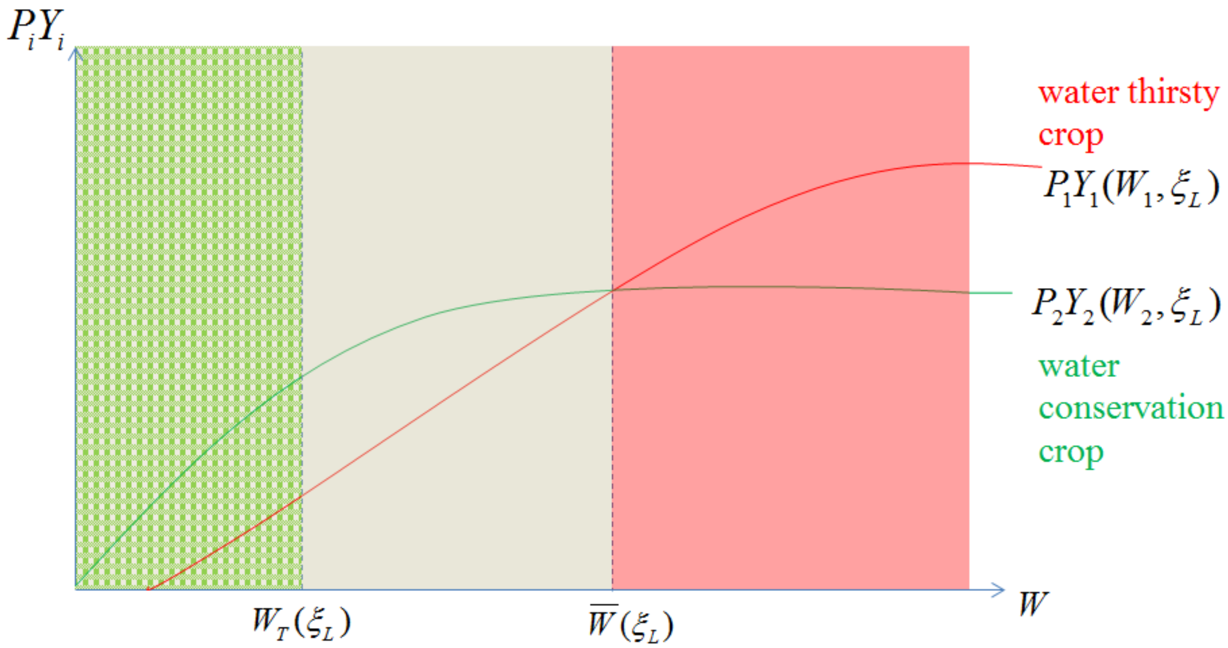

Figure 3(a): Illustration of optimal water usage change with two crops: low irrigation efficiency

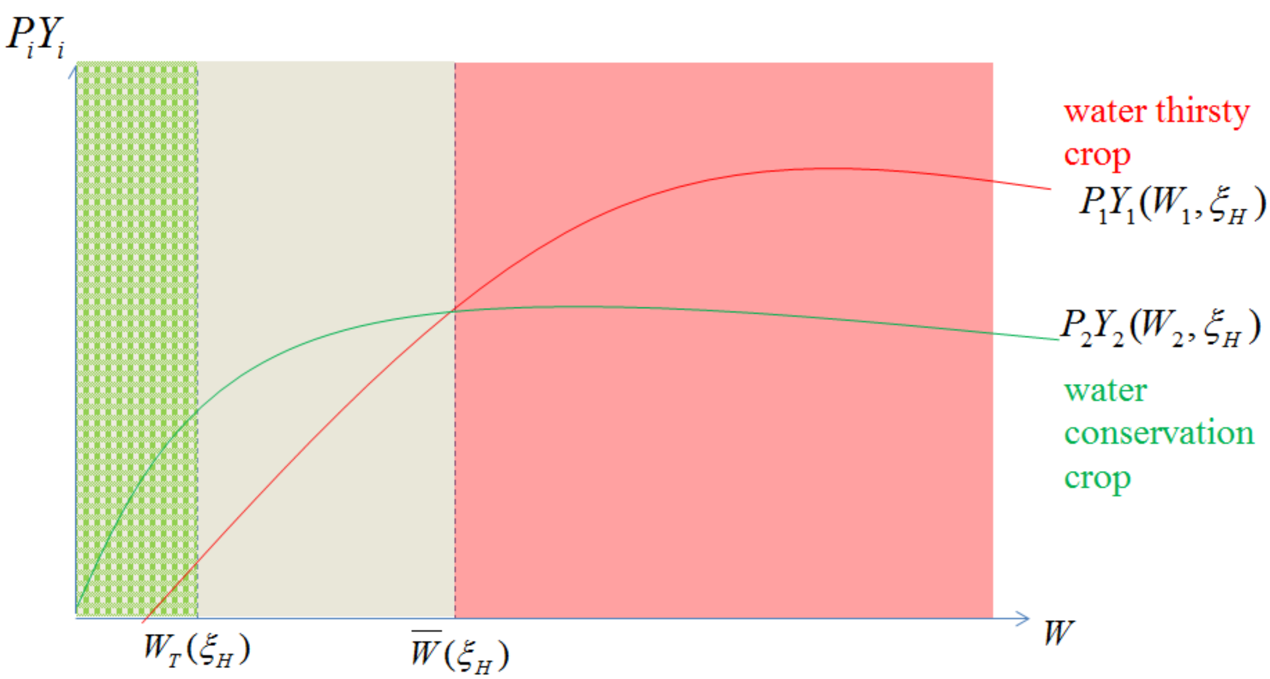

Figure 3(b): Illustration of optimal water usage change with two crops: high irrigation efficiency

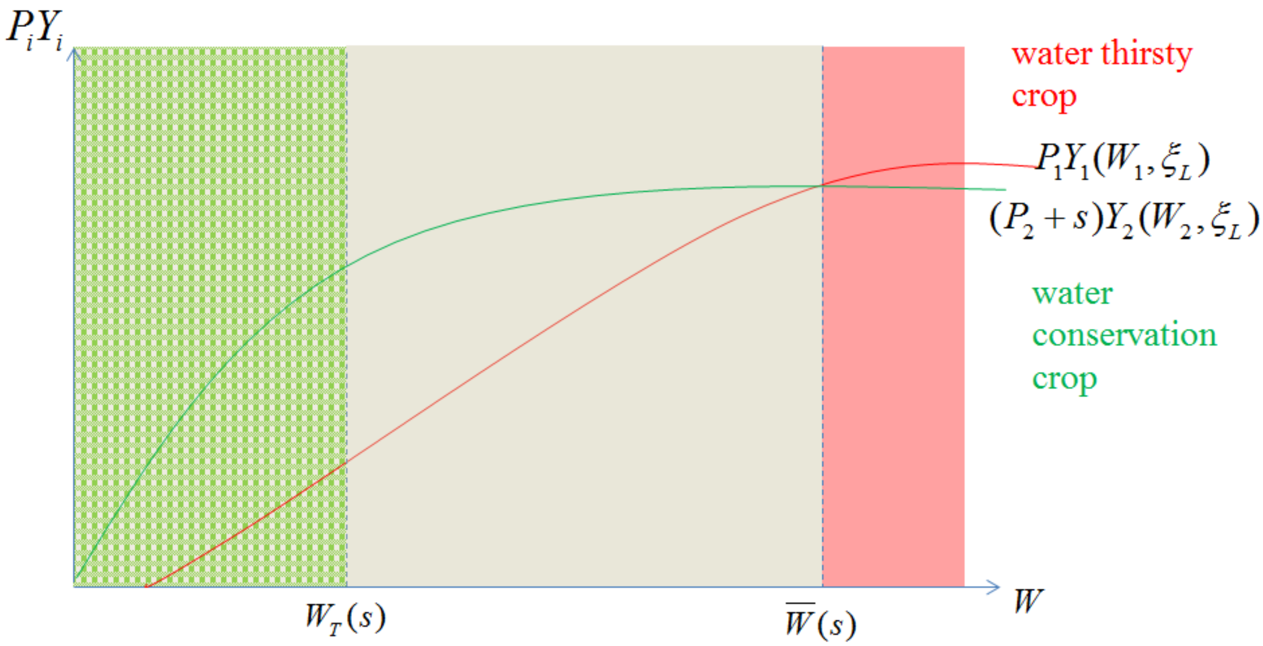

Figure 3(c): Illustration of optimal water usage change with two crops: subsidy on water-conservation crop.