Evaluating Economic Efficiency of a Water Buyback Program:

The Klamath Irrigation Project

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ABSTRACT

Increasing scarcity of water resources in many regions is likely to give rise to disputes similar to those observed in the Klamath region of Oregon and California where irrigation water buyback programs have been implemented to reduce irrigation diversions with the purpose of securing required instream flow for aquatic habitat. In this study using a mathematical programming approach we compare a direct water buyback program with an indirect, land idling based, program for securing required amount of water. We show that land idling based programs can be costlier than direct water buyback programs. Compensation for water idling directly, unlike land idling based programs, ensures that marginal water units with the lowest derived demand values are removed from production first.

Key words: Water demand, Irrigation, Water Buyback.

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Since the 1970s the focus of water management policies in the US has shifted from supply augmentation towards reallocation of existing supplies to meet competing demands (Chong and Sunding, 2009). Water acquisition and buyback programs are intended to reallocate existing water supplies among competing uses to correct under provision of public goods such as biodiversity and endangered species habitat. The Klamath Water Bank, California's Environmental Water Account, and Washington State's Walla Walla Mitigation Exchange are examples of programs that lease or buy water for environmental purposes. This paper evaluates the cost effectiveness of the 2010 Klamath Irrigation Project (KIP) water buyback program. The program solicited bids for idling land to reduce surface irrigation water diversions in accordance with the Endangered Species Act (ESA) mandate for aquatic habitat provision.

We demonstrate that an irrigation water buyback based on land idling bids, versus direct water idling[i], requires expenditures in excess of the value of irrigation water in agricultural production. To illustrate this disparity, we first provide a theoretical illustration of land versus water idling. Next, the derived demand for irrigation water in the Klamath Irrigation Project is empirically estimated. The derived demand is used to compare the observed expenditures in the 2010 water buyback program to the corresponding estimated derived value of irrigation water. The model is also used to compare the estimated expenditures from direct water idling to the estimated expenditures from a land idling based water buyback program. The analysis seeks to make two contributions to the water acquisition literature. First, our methodology illustrates a practical empirical framework that regulators can use to value irrigation water. Second, the disparity between actual 2010 buyback expenditures and the estimated marginal value product (MVP) of surface irrigation water is estimated. This difference can be attributed to the design of the water buyback program and/or to the premium necessary to induce participation in a water buyback auction (Burke, 2002; Burke et al. 2004).

The central argument of this paper is that, barring transaction costs including monitoring and enforcement, land idling buyback programs are costlier than paying directly for reductions in diversions of surface water. Land idling bids include opportunity costs of both land and water as inputs in production. In contrast, a water buyback program based exclusively on water idling avoids expenses associated with idling land as a factor of production. In addition, idling a parcel of land with its appurtenant water right idles water with high MVP as well as water with lower MVP. In contrast, a program which pays for water directly, rather than indirectly via land idling, ensures that water with the lowest marginal derived demand values is purchased first. Cost inefficiency results from the foregone value of removing land from production and the decreasing marginal productivity of irrigation water.

This study examines potential differences in expenditures on securing reductions in diversions not accounting for monitoring and enforcement costs. Monitoring and enforcement costs of land based idling programs are low. In contrast, direct water idling programs require investment in water meters, gauges, or other technologies[ii]. Thus, if monitoring costs exceed the savings that may be realized by switching from land idling to direct water use reduction based programs, then direct water idling programs are not justified. While benefits of switching from land based idling to direct water idling during a water shortage in any given year may not exceed costs of monitoring, repeated water shortages requiring repeated buybacks may justify investments in monitoring infrastructure. Furthermore, monitoring infrastructure can provide benefits in addition to the facilitating monitoring and enforcement in water buyback programs.

The paper is structured as follows: Section 2 provides necessary background on the study area; Section 3 provides a theoretical illustration of land idling based vs. direct water buybacks; Section 4 describes the empirical approach; Section 5 discusses the data and data sources; Section 6 presents results and Section 7 provides discussion and concluding statements.

Study Area and Background

The Klamath Irrigation Project (KIP, Figure I), located on the Oregon/California border, was created in 1905 under the provisions of the 1902 Reclamation Act to provide irrigated agricultural land for homesteading (USBR, 2009; Hathaway and Welch, 2002). KIP includes approximately 200,000 acres of farmland with approximately 1,400 individual farms and ranches which principally produce pasture, alfalfa, other hay, barley, wheat, oats, potatoes, and onions (USBR, 2005-2009). Surface water from Upper Klamath Lake, Clear Lake, and Gerber Reservoir is used to irrigate Project and non-Project land in the Klamath Basin, provide in-stream flows for endangered fish habitat, and water for two wildlife refuges. The Klamath Basin is home to 19 species of native fish, including the endangered Coho salmon and the Lost River and Shortnose suckers, which support tribal, sport, and commercial fisheries (Lewis et al., 2004). The decline of endangered fish species has been attributed to water management, water quality, loss of habitat, overfishing, and other causes (Lewis et al., 2004).

The U.S. Bureau of Reclamation (USBR) manages surface water deliveries to Project irrigators from water stored in Upper Klamath Lake, Gerber Reservoir, and Clear Lake Reservoir. Prior to releasing surface water for irrigation, USBR must comply with Endangered Species Act mandates in the Biological Opinions of U.S. Fish and Wildlife Service (USFWS) and National Marine Fisheries Service (NMFS). The USFWS' Biological Opinion recommends a minimum elevation for Upper Klamath Lake to protect the Lost River and Shortnose suckers. Similarly, NMFS' Biological Opinion recommends minimum in-stream flows in the Klamath River to protect endangered Coho salmon (Hathaway and Welch, 2002).

Water management in the Upper Klamath Basin has been contentious. Prior to 2001, irrigation curtailments during low flows were limited to low-priority Project water contracts (Markle and Cooperman, 2002). However, the severity of the 2001 drought necessitated the inclusion of high-priority water contracts in some areas of the Project. This curtailment attracted significant public attention, protests, and calls for annulment of the Endangered Species Act (Jaeger, 2004). The 2001-2002 surface water curtailment of KIP irrigators, as administered by the USBR, has been addressed by Braunsworth, et al. (2002), Jaeger, (2004), Boehlert and Jaeger, (2010), and Adams and Cho, (1998). The curtailment resulted in estimated losses of \$27 to \$46 million in net revenue for KIP agricultural production (Jaeger, 2002; 2004). To alleviate the economic impact of irrigation curtailment, \$35 to \$37 million was paid in emergency government transfers (Jaeger, 2002). Drought induced high water temperatures and low in-stream flows along with irrigation withdrawals contributed to the 2002 die-off of an estimated 34,000 Chinook salmon (Guillen, 2003; Lewis et al., 2004) injuring tribal communities and commercial fisheries (Powers et al., 2005).

Several recommendations have been proposed to mitigate the effect of water shortages including: simplifying and strengthening water property rights structure (Slaughter and Wiener, 2007), allowing for off-Project water purchases and trades (Jaeger, 2004), water banks (Burke et. al., 2004; Lewis et al., 2004), and tradable environmental rights (Tisdall, 2010). Legal barriers preclude enforcing ESA-related surface water use restrictions on non-Project lands (Jaeger, 2004). Furthermore, complex guidelines for water transfers in California and the absence of proper water right structure in the Oregon portion of the Klamath Project made water market transfer programs difficult to implement (Burke et. al., 2004). Jaeger (2004) estimates that water market mechanisms could have reduced the impact of the 2001 curtailment on farm incomes by as much as 75%. Most of the mitigated impact stems from allocating water to Project areas while reducing irrigation on less productive outside the Project. In addition, surface irrigation water shortages might be mitigated by deficit irrigation (Adams and Cho, 1998) and increasing groundwater pumping to supplement surface water use (Boehlert and Jaeger, 2010). Groundwater pumping in the KIP has risen significantly in the years following the 2001 shortage, but the availability and sustainability of groundwater pumping has not been fully investigated (USGS, 2005). In the upper Klamath Basin, groundwater is a major component of stream flow and groundwater use may affect stream flow through reductions in surface water discharge (Gannet et al., 2010). Canal leakage and percolation of irrigation water are not considered to be significant sources of aquifer recharge overall (Gannet et al., 2010).

In 2010, USBR reduced expected deliveries to irrigators in the KIP to comply with the Biological Opinions of the U.S. Fish and Wildlife Service and the National Marine Fisheries Service (USBR, 2010a). To mitigate irrigation shortages in the KIP, additional funding was allocated to the Klamath Water and Power Authority (KWAPA) which manages water supplementation, groundwater pumping, and land idling programs. The Land Idling Program reduce surface water use by compensating irrigators for forgoing irrigation on all or part of their land. In 2010, KWAPA accepted sealed bids to idle 18,000 acres at a cost of $3.2 million. Accepted bid amounts ranged from $0 to $225 per idled acre with a weighted average bid of $176. Between 36,000 to 45,000 acre feet (AF) of surface water was purchased at a cost $70 to $88 per AF (assuming 2 to 2.5 AF of surface water per acre[iii]).

Burke et al. (2004) use positive mathematical programming (PMP) to simulate the value of water purchases from KIP irrigators. Using the 2003 Water Bank Program offer price of $75/AF as a reference point, they estimate a “participation factor” cost of $15/AF, or approximately 25% to 40% of the price. “Participation factor” is defined as the monetrary incentive needed to encourage participation in the water buyback program from the point of indifference between using and selling water (Burke et. al., 2004). They also conclude that the irrigators’ demand curve is relatively elastic as a result of the small portion of high valued crops (e.g., onions, potatoes, mint) planted during a given year. Thus, lowering the Water Bank Program offer of $75 to $73 per acre foot could result in a reduction of water offers from 60,000 to 30,000 AF (Burke et al., 2004).

Slaughter and Wiener (2007) argue that USBR purchases of Klamath Basin irrigation water in 2002 were priced well above the estimated return on water. Boehlert and Jaeger (2010) evaluate the effects of adjustments in ESA requirements, expansions in groundwater pumping capacity, and extended water transfers, on economic impacts of water shortages in the Klamath Basin. They use Ricardian rent farmland market prices to estimate marginal value of water per acre foot ranging from \$9 on the poorest soils (class V) to \$105 on the best soils (class I). Using an LP model of four representative farms and crop rotations in the Project Adams and Cho (1998) estimate the marginal value of water in the Klamath Basin to be between \$22 and \$79 per acre foot.

THEORETICAL ILLUSTRATION

The difference between a program which pays for land idling to reduce water diversions and a program which pays for reductions in water diversions directly can be illustrated using the construct of an isoprofit function. The difference between the two programs can be represented in terms of compensation which would be required to achieve a targeted reduction in water diversions under each program., For theoretical illustration define $\pi(w,a)$ as isoprofit lines, net of all costs of production, for agricultural producers whose activities are constrained by the maximum amount of available irrigation water ($\overline{w}$) and maximum land acreage ($\overline{a}$). Define r_1 and r_2 as pseudo scale lines[iv] (Debertin 2012). With no water use reduction policies producers' profits are $\pi(\overline{w},\overline{a})$. The regulator's objective is to reduce water withdrawals in the region from $\overline{w}$ to $\overline{w}-\tilde{w}$. To do so, the regulator can either directly compensate irrigators not to use $\tilde{w}$ amount of water, and let the producer select the corresponding optimal a^* (scenario 1), or compensate the producers to idle enough land to reduce water withdrawals by $\tilde{w}$ (scenario 2). For incentive compatibility, the regulators expenditures for encouraging producers' participation in the buyback program have to be greater than or equal to the difference in producers' profits with and without participation in the program.

In scenario 1, producers maximize $\pi^1\left(\overline{w}-\tilde{w},a\right)$ with respect to acreage of cultivated land given a $\tilde{w}$ reduction in water use, subject to $a \le \overline{a}$. If for optimal $a^*|_{(\overline{w}-\tilde{w})}$ the acreage constraint is binding, $a^* = \overline{a}$, then $\pi^1 = \pi^1\left(\overline{w}-\tilde{w},\overline{a}\right)$. If the acreage constraint for optimal $a^*|_{(\overline{w}-\tilde{w})}$ is not binding then first order conditions $\pi_a = \partial\pi\left(\overline{w}-\tilde{w},a\right)/\partial a = 0$ can be used to obtain $a^* = a^1 = \hat{a}_{\pi_a}\left(\overline{w}-\tilde{w}\right)$ where $\hat{a}_{\pi_a}$ is an explicit expression for a^* from $\pi_a(w,a)=0$. Hence, in scenario 1 change in profits can be expressed as:

$$\Delta\pi^1 = \pi\left(\overline{w},\overline{a}\right) - \pi^1\left(\overline{w}-\tilde{w},\hat{a}_{\pi_a}\left(\overline{w}-\tilde{w}\right)\right),\text{ where } \hat{a}_{\pi_a}\left(\overline{w}-\tilde{w}\right) = \begin{cases} \overline{a},\ if\ \hat{a}_{\pi_a}\left(\overline{w}-\tilde{w}\right) \ge \overline{a} \\ \hat{a}_{\pi_a}\left(\overline{w}-\tilde{w}\right),\ otherwise \end{cases} \quad (1)$$

In scenario 2, producers maximize profits $\pi^2\left(w,a\right)$ with respect to applied irrigation water depending on the amount of idled acreage, subject to $w \le \overline{w}$. Producers choose the optimal amount of irrigation water, w^* , corresponding to the amount of planted acres. The objective of the regulator is to incentivize the producer to idle enough acres to cause a desired reduction in water use from $\overline{w}$ to $\overline{w}-\tilde{w}$. If for a' planted acres the water constraint is binding, $w^* = \overline{w}$, then idling $\overline{a}-a'$ acres produces no reductions in water use. In this situation $\overline{w}$ amount of water gets redistributed across fewer acres with a lower marginal value product then prior to redistribution. Reduction in cultivated acreage does not reduce water use until enough acres are idled to ensure that acres remaining in production receive profit maximizing amounts of irrigation water. At this point further land idling will free up water which would not be profitable to apply to acres remaining in production and total water use across all acres will fall below $\bar{w}$. This occurs when pseudo scale line r_1 falls below $\bar{w}$ (Figure II). After this point further reduction in acreage will generate a water use reduction equal to the distance between r_1 and $\bar{w}$[v]. From first order condition $\pi_w = \partial \pi(w,a) / \partial w = 0$ we can get acreage for which optimal water use is $\bar{w}-\tilde{w}$, $a^2 = \hat{a}_{\pi_w}(\bar{w}-\tilde{w})$. Hence, in scenario 2, change in profits can be expressed as:

$$\Delta\pi^2 = \pi(\bar{w},\bar{a}) - \pi^2\left(\bar{w}-\tilde{w}, \hat{a}_{\pi_w}(\bar{w}-\tilde{w})\right) \qquad (2)$$

It can be easily seen that $\Delta\pi^2 > \Delta\pi^1$ because a^1 in scenario 1 is derived from $\pi_a(\bar{w}-\tilde{w},a) = 0|_{w=\bar{w}-\tilde{w}}$ corresponding to acreages defined by either pseudo scale line r_2 or $\bar{a}$ depending on the magnitude of required water use reduction $\tilde{w}$. On the other hand, a^2 in scenario 2 is obtained from $\pi_w(w,a) = 0|_{w=\bar{w}-\tilde{w}}$ corresponding acreages defined by pseudo scale line r_1. Given that in both scenarios water use is $\bar{w}-\tilde{w}$, scenario 2 produces lower profits than scenario 1because isoprofit π^1 is preferable to isoprofit π^2 (Figure II).

MODEL

We employ crop and soil specific agronomic production functions expressed in terms of per acre applied irrigation water. The model also includes 134 soil types with respective productivities and acreages to represent variability of soil productivity in the KIP (Figure I). The model thus allows flexibility in production decisions in term of per acre water application as well as planting decisions per crop and soil combinations. As a result, the MVP of water is directly computed at various levels of water availability producing derived demand for irrigation water. This specification allows for the analysis of the program under assumptions of deficit irrigation as well as no deficit irrigation (English and Raja, 1996, Cortignani and Severini 2009, Burke, Wallander, and Adams, 2004). GIS data is combined with the profit maximization model and in lieu of a Leontief production technology, used in linear programs, agronomic crop production functions that exhibit decreasing marginal physical product for applied water are used (Martin, Gilley, and Supalla, 1989; Contor et al. 2008).

The profit maximization model calculates the MVP of water under various levels of surface water availability corresponding to various water buyback targets. Irrigators maximize profits by choosing planted acreages of various crops on various soils, as well as levels of applied irrigation water depending on the deficit irrigation assumption scenario. Irrigators face the constraints of soil type acreage availability, water availability, and crop rotation restrictions reflecting managerial and agronomic requirements. Total profits for the KIP are total revenue (yield times crop price) minus variable costs of production. Variable costs are split into irrigation costs and non-irrigation costs. The profit function to be maximized is:

$$\pi = \sum_{c,s,i,w,k} a_{c,s,i,w,k} * \left[f_{c,s,i,w,k}\left(w_{c,s,i,w,k}\right) * P_{c,k} - IrrCo_{c,i,w,k} * w_{c,s,i,w,k} - Co_{c} \right] \qquad (3)$$

where c is crop type; s is soil type; i is irrigation technology; w is water source; k is either the California or Oregon side of the irrigation project; a is acreages of various crops planted on various soils irrigated using either surface or groundwater with either gravity or sprinkler irrigation technology in either California or Oregon; w is the corresponding applied water per acre; $f(w)$ is the per acre crop yield; P is crop price; $IrrCo$ are variable costs of irrigation which include costs of pumping, labor, and machinery/repair, and vary to account for the differences across crops, irrigation technology, water sources and states; and Co is per acre non-irrigation variable costs of production by crop type and includes non-irrigation related variable production costs like labor, fertilizers, pest management, fuel, etc.

The crop production function $f_{c,s,i,w,k}(w_{c,s,i,w,k})$ varies by crop, soil type, irrigation technology, water source, and state. Yield is invariant to water source. However, water source does affect irrigation costs via additional energy costs associated with groundwater pumping. The production function (Martin, Gilley, and Supalla 1989) is:

$$f_{c,s,i,w,k}\left(w_{c,s,i,w,k}\right)=Yd_{c,s,k}+\left(Ym_{c,s,k}-Yd_{c,s,k}\right)\left[1-\left(1-\frac{w_{c,s,i,w,k}}{Im_{c,s,i,k}}\right)^{\left(\frac{Im_{c,s,k}}{ETm_c-ETd_c}\right)}\right] \quad (4)$$

where Ym is crop yield at full irrigation; Yd is non-irrigated yield (dry yield)[vi]; w is irrigation depth or amount of water applied per acre; Im is irrigation depth at full irrigation or amount of water applied per acre at full irrigation required to produce Ym ; ETm is evapotranspiration at full irrigation; and ETd is evapotranspiration at non-irrigated yield or dry yield.

Profits are maximized subject to land availability, crop rotation, and water availability constraints. Planted acreage must be less than or equal to the land available for production within each state's distribution of acres across soil types, irrigation technologies, and water sources. While some land can be irrigated only using surface water, other parts of the KIP can be irrigated using either surface or ground water. Constraints (5) and (5) restrict total planted acreage and limit ground water acreage to be no more than the amount of land that can be irrigated using either surface or ground water. In this formulation “ground” refers to acreages that can be irrigated either using groundwater or using surface water. All other lands within the project are assumed to be irrigated only using surface water. The formulation allows for substitution of production between surface and groundwater irrigation in some areas of the KIP.

$$\sum_{c}\sum_{w} a_{c,s,i,w,k} \leq \sum_{w} Land_{s,i,w,k} \ \forall\, s,i,w,k \qquad (5)$$

$$\sum_{c} a_{c,s,i,w="ground",k} \leq Land_{s,i,w="ground",k} \ \forall\, s,i,k \qquad (6)$$

Crop rotation constraints are imposed based on historically observed variability of planted crop acreages to reflect agronomic, farm management, and other factors which affect planting decisions. Crop planted acreage is restricted to be a convex combination of historically observed crop mix proportions (McCarl et al., 1982; Elbakidze et al., 2012). These proportions were taken from KIP crop reports provided by the U.S. Bureau of Reclamation, Klamath Basin Area office, which split planted acreage between the Oregon and California sides of the Project. Constraints for convex combinations of crop rotations are:

$$\sum_{s,w,i} a_{c,s,i,w,k} = \sum_{y} \lambda_{k,y} * CropMix_{c,k,y} \qquad \forall\, c,k \qquad (7)$$

$$\sum_{y} \lambda_{k,y} = 1 \qquad \forall\, k \qquad (8)$$

where y is a historical year from observed crop mix data; $CropMix_{c,k,y}$ is historically observed acreage of each crop by state in year y; $\lambda_{k,y}$ is a choice variable restricted to the bounds [0 : 1] and can be interpreted as the proportion of simulated acreage that is planted consistent with the crop acreage distribution observed in year *y*. In other words, $\lambda_{k,y}$ shows the percentage of planted acreage simulated to be planted in similar crop mix proportions as in historical year *y*. This specification constrains the simulated planted acreage to fall within the bounds of planted crop mix acreages observed in recent years and indirectly forces the solution to obey various agronomic and managerial rotation constraints and other restrictions which affect planted acreage decisions in addition to water and land availability constraints. For example, in practice planting decisions take into account crop rotation requirements based on pest management and soil quality considerations. In the absence of constraints capturing such rotation requirements the optimization model will over allocate land for more profitable crops and under allocate land for less profitable crops relative to crop mixes observed in practice.

Shadow prices from the surface water availability constraint are used to obtain a series of MVP estimates corresponding to various levels of surface water availability. The constraint maintains that applied surface water must be less than or equal to surface water availability. $Water_{w='surface'}$ is varied across multiple model runs to reflect different levels of surface water availability and to generate corresponding MVP values[vii] which are used to construct derived demand for irrigation water.

$$\sum_{c,k,s,i} w_{c,s,i,w=\text{'surface'},k} * a_{c,s,i,w=\text{'surface'},k} \leq Water_{w='surface'} \qquad (9)$$

DATA

The model includes the following crops: alfalfa, oats, barley, wheat, hay, potatoes, peppermint, onions, and pasture. Crop prices are obtained from the U.S. Bureau of Reclamation 2005-2009 Klamath Irrigation Project crop reports provided by the Klamath Basin Area Office. Crop prices are defined separately for each state (California and Oregon) in the KIP. Per unit prices of each crop over 2005-2009 are CPI adjusted for inflation, expressed in 2010 dollars, and averaged for each state over years.

Production costs, from crop budget reports (Oregon State University; University of California, Davis), are bifurcated into irrigation and non-irrigation related variable costs[viii]. Irrigation costs include fixed per acre costs (independent of rate of irrigation), which includes operation and maintenance (O&M) and equipment rental[ix], and variable costs (depending on the amount of water used per acre), which includes water charges[x], electricity, labor, and repair costs. Electricity, labor, and repair costs are obtained from crop budget reports in dollars per acre and vary by irrigation technology. These costs are converted to a per acre foot basis by dividing the per acre cost by the number of acre inches reported in the crop budget report, and multiplying by 12 inches. Irrigation costs vary depending on water source, state, and irrigation technology. Although production costs vary by soil class, cost and return estimates are not available at the resolution of soil class. Therefore, representative production costs are used. Variability across soil classes is reflected in the production capability of various soils.

Historical planted crop mix acreages in equation (7) are taken from the USBR crop reports. The nine crops in the model represent over 98% of planted acres. Onions and peppermint were included because they are high value crops (Burke et. al., 2004).

Parameters for the Martin, Gilley, and Supalla (1989) production functions are generated using data from various sources. Maximum observed yields were obtained from Oregon State University extension agents. United State Department of Agriculture's Natural Resource Conservation Service (NRCS) data also reports yields per soil type. The soil type with the greatest yield in the NRCS data is assigned maximum yield as reported by OSU extension agents. Maximum yields for the rest of the soil types are estimated proportionally according to relative yields in the NRCS data. Precipitation data come from the U.S Department of the Interior's AgriMet website[xi]. Figure III provides an overview of production function parameterization. Details can be found in the Appendix.

Land constraints are generated by overlaying GIS maps and vary by soil type, water source, and irrigation technology. The data includes a GIS Project boundary (USBR, Figure I), GIS soil data, GIS groundwater use data, and acres by irrigation technology. Soil types, corresponding acreages, and land productivity are taken from the U.S. Department of Agriculture's soil data mart (NRCS). There are a total of 134 NRCS soil types within the KIP, 73 and 61 in Oregon and California respectively. Calculated acreages of each soil type by irrigation technology and water source in each state are used as upper bounds in Equation (5). GIS maps from California[xii] and Oregon[xiii] contain groundwater data, which is used in combination with GIS data on soil type distribution to select only those soil types that can be irrigated by surface and groundwater[xiv]. This allows for shifts of production from surface irrigation to groundwater irrigation as surface water is idled. All other areas within the project are considered to be irrigated by surface water only. In lieu of unavailable spatially explicit data on distribution of gravity versus sprinkler irrigation the overall distribution of gravity and sprinkler irrigated land was obtained from the Klamath Water Users Association (H. Cannon, personal communication, 2011). Approximately 40% and 8% of irrigated acres utilize sprinkler irrigation in Oregon and California, respectively. The proportion of sprinkler to flood irrigation is assumed to be the same across surface and groundwater sources.

RESULTS

The model simulates water use under various levels of surface water availability to arrive at corresponding shadow prices representing the MVP of surface irrigation water. The surface water constraint is iteratively relaxed to 600,000 AF to obtain derived demand curves for surface irrigation water in the Project. Gross project diversions for KIP from 1961 to 2003 have been as high as 500,000 AF (USGS, 2005). Facing water shortages farmers can adjust the soil and crop portfolio and, at least in theory, can also adjust irrigation intensity i.e. deficit irrigation. In early spring, in advance of an announced water shortage, farmers decide where (i.e. soils) and what crops to plant and later in growing season irrigation intensity (i.e. deficit irrigation). Lacking information or evidence about the extent of deficit irrigation in this region, derived demand curves were obtained with and without deficit irrigation. With no deficit irrigation, the choice variables are planted acreages of various crops on various soil types with per acre applied water fixed at the rate equal to the biologically optimal (unconstrained) irrigation levels per acre (I_m). The producers are assumed to respond to reduced availability of surface irrigation water only by adjusting planted crop acreages. With deficit irrigation the producers can adjust crop planted acreages as well as per acre applied irrigation water for various crops on various soil types.

Shadow prices from the two scenarios are used to statistically estimate the corresponding derived demands for surface irrigation water. Table I provides estimated coefficients for fitted curves (Figures IVa and IVb) under deficit and no deficit irrigation scenarios respectively. The Box-Cox specification (Equation 10) is used to identify the appropriate functional form in each scenario:

$$y_j^{(\theta)} = \beta_0 + \beta_1 x_j \qquad (10)$$

where x_j are different surface water availability bounds, y_j are shadow prices obtained from running the model at corresponding levels of surface water availability, and

$$y^{(\theta)} = \begin{cases} \frac{y^{\theta}-1}{\theta} & if\ |\theta| > 0 \\ ln(y) & Otherwise \end{cases}. \qquad (11)$$

Based on statistical significance of estimated parameters (Table I), the derived demand curves (Figures IVa and IVb) have the following form:

$$y = (\theta\beta_0 + \theta\beta_1 x + 1)^{1/\theta} \qquad (12)$$

To obtain marginal value of additional x^* units of irrigation water (MVP_{x^*}) at x' level of applied irrigation water, Equation 10 is integrated between x' and $x' + x^*$, or

$$MVP_{x^*} = \int_{x'}^{x'+x^*} (\theta\beta_0 + \theta\beta_1 x + 1)^{\frac{1}{\theta}}\, dx$$

$$= \left.\frac{(\theta\beta_0 + \theta\beta_1 x + 1)^{\frac{1}{\theta}+1}}{(1+\theta)\beta_1}\right|_{x'+x^*} - \left.\frac{(\theta\beta_0 + \theta\beta_1 x + 1)^{\frac{1}{\theta}+1}}{(1+\theta)\beta_1}\right|_{x'} \qquad (13)$$

In 2010, KWAPA provisionally accepted land idling applications with a price tag of \$3,227,000. This program produced 18,312 acres of idled land (KWAPA, 2010). Assuming an applied irrigation water rate of 2.5 AF per acre, the irrigation reduction totals approximately 45,000 AF or an average of \$71 per AF of compensation for idling.

The estimated MVP of irrigation water can vary depending on what amounts of irrigation water, or corresponding water rights, are perceived as eligible for idling. The value of idled water depends on the point of reference on the derived demand curve. Three points of assumed availability of eligible water rights (x') for idling are used for comparison reference: low availability of water (x' =200,000 AF), medium availability (x'=390,000 AF), and high (x' =500,000). Equation 11 is used to estimate a marginal value of $x^* = 45{,}000$ AF of surface irrigation water at each of the three assumed points of reference. These estimates are reported in Table I as $MVP_{x^*}^{low}$, $MVP_{x^*}^{med}$, and $MVP_{x^*}^{high}$ respectively for deficit as well as no deficit irrigation scenarios.

Estimated MVP_{x^*} ranges between \$0.78 million and \$11.3 million depending on the point of reference for x' and the deficit irrigation assumption. Three of the six estimates of MVP_{x^*} are greater than the actual expenditure for land and water idling observed in 2010 bids. The irrigators would not be willing to accept land idling compensation which falls short of MVP values unless they expected that they would likely not receive their usual water deliveries under the BOR water budget. The three scenarios with MVP values higher than the total of submitted bids are: the deficit (\$6.6 million) and no deficit (\$11.3 million) irrigation scenarios for low (x' =200,000 AF) availability of eligible water rights, and the medium availability of eligible water rights (x' =390,000 AF) with no deficit irrigation assumption (\$5.5 million). These outcomes are not surprising given high marginal physical product and high marginal value of irrigation water at low levels of use. These results imply that the irrigators submitting idling bids did so either a) assuming a point of reference which exceeds 200,000 AF despite expectations that deliveries beyond 200,000 were unlikely[xv], and/or b) hoping to get some compensation, even if lower then MVP, for deliveries that would likely go unfulfilled.

In the remaining three scenarios, the values of idled water are $0.78 million in the high water right eligibility and deficit irrigation scenario, $1.7 million in the medium water right eligibility and deficit irrigation scenario, and $2.87 million in the high water right eligibility and no deficit irrigation scenario. The scenario with no deficit irrigation and 500,000 AF as reference point produces the closest estimate to $3.2 million which was spent on land idling in 2010.

The MVP curves of land were estimated by iteratively increasing the upper bound of total surface water irrigable acreage and obtaining corresponding MVP values as described above assuming deficit and no deficit irrigation. The obtained land MVP curves are used to estimate the value of land that would need to be idled to produce 45,000 AF in reduced surface water diversions at various reference points for water deliveries. The estimates of idled land values corresponding to scenarios in Table I are provided in Table II with and without deficit irrigation scenarios. Consistent with theoretical illustration, the values of land which would have to be idled to produce 45,000 AF reduction in surface water diversions are greater than the value of 45,000 AF of surface irrigation water across all corresponding scenarios. For example, if water diversions are to be reduced from 500,000 AF to 455,000 AF land idling based program would require $2.37 million, while the value of 45,000 AF of water is $0.88 million under deficit irrigation scenario. Under no deficit irrigation, the value of idled land to reduce diversions from 500,000 AF to 455,000 AF is $3.3 million, while the value of 45,000 AF of surface irrigation water is $2.87 million. Depending on the scenario, the value of land which needs to be idled to reduce diversions by 45,000 AF exceeds the value of 45,000 AF of surface water by anywhere from $473,000 to $4.2 million. These differences translate into 6 to 300 percent difference between corresponding values of idled land and 45,000 AF of surface irrigation water. The differences are significantly more pronounced in deficit irrigation scenarios than in no deficit irrigation scenarios.

The scenario with no deficit irrigation and the reference point of 500,000 AF produces estimates which are closest to the observed bids of $3.2 million. In this scenario, the value of land needed to reduce surface water use by 45,000 AF is $3.3 million. On the other hand, the value of 45,000 AF of reduced irrigation water diversions is $2.87 million.

Based on estimated values of 45,000 AF of surface irrigation water in Table I, the value of surface irrigation water is $17, $40, $64, $122, $147, and $146 per AF depending on deficit irrigation assumptions and the reference point on the demand curve. These values are in the range of previous estimates: $22 to $79 per AF (Adams and Cho, 1998) and $9 to $105 per AF (Boehlert and Jaeger, 2010). The scenarios with lower estimates of the values of idled land and/or water than the observed total of bids in the 2010 KWAPA water buyback program are consistent with prior literature (Burke et. al., 2004; Boehlert and Jaeger, 2010) where purchasing price of irrigation water exceeded the value of irrigation water in agricultural production.

The difference between the estimated marginal value product and the actual total value of corresponding bids may be attributed to the discontinuity of the land idling program, dynamic effects of multi-year contracts, incentive compatibility of the bidding auction mechanism, and a "participation factor." In our empirical estimation, in a buyback program which pays directly for water rather than indirectly via land idling, water with the lowest marginal value is retired first. The discontinuity in the land idling mechanisms, similar to the 2010 KWAPA buyback program, forces the submission of higher valued applied irrigation water on a particular idled parcel before less valuable last acre foot of applied water from a different parcel is considered for idling. In our specification, marginal value product estimates in Table I are obtained without requiring land idling. In other words, our specification estimates the true marginal value product of irrigation water when water use is not tied to land idling. Least valuable marginal units of water are consistently idled before relatively more valuable marginal units. In contrast, the KWAPA water buyback program based on land idling, solicits bids for land idling rather than for water directly. As a result, submitted bid values do not necessarily correspond to the least valuable units of irrigation water. Instead, submitted bids include high as well as low marginal value units of irrigation water that would have been used for production on the idled parcel of land. Submitted bids for land idling may also include net present value of multi-year contracts, which may be lost as a result of land idling.

The "participation factor" could include family and tradition values attached to agricultural enterprises, social ties and community status, or participation transaction costs. Burke, Adams, and Wallender (2004) estimate that the participation factor can increase the costs of water buyback programs by 25 - 40% over the value of irrigation water. This factor could be contributing to the divergence between our estimates of the marginal value of irrigation water and total bid amount from the 2010 water buyback program.

DISCUSSION AND CONCLUSIONS

In this paper, we illustrate the differences between land idling based irrigation water buyback programs and the value of irrigation water as a factor of production in irrigated agriculture. Redesigning water buyback programs may reduce the costs of securing water for habitat preservation. Conditional on technological feasibility and associated costs, a program that compensates for reduced irrigation water directly rather than indirectly via compensating for idled land, may reduce program costs. This cost reduction maybe especially significant if farmers practice deficit irrigation. A program compensating for reductions in irrigation water use directly would be more consistent with the marginal value product of irrigation water, as estimated in this study. Such mechanism would avoid non-monotonicity of irrigation water value that emerges due to the land idling-based structure of the water buyback program implemented by KWAPA. The explicit consideration of the "participation factor" may assist policy makers in estimating the costs of preserving specified amounts of surface water for lake elevation requirements or in-stream flow amounts imposed by the USFW and NMFS Biological Opinions.

The USBR 's 2010 buyback program to reduce diversions of surface water in the KIP is used as a case study under two assumed water management scenarios. The first is a no deficit irrigation scenario where irrigators choose only the number of acres of various crops planted at full irrigation. The second is a deficit irrigation scenario where irrigators choose per acre irrigation amounts as well as planted acreages of various crops. The USBR 2010 buyback program yielded approximately 45,000 AF of surface water reduction at a cost of $3.2 million. The approximate cost of the buyback was $71 per AF, which falls within the range of values estimated in this study and is most comparable to $64 per AF estimate which is obtained in the direct water idling scenario with no deficit irrigation assumption and 500,000 AF as the amount of water eligible for idling.

In general, the ease of water transfers facilitates the allocation of water to the most valuable uses (Slaughter and Wiener, 2007). However, the combination of complex water property rights structure (Mathews, 2004) and the relative abundance of surface water in previous years has contributed to the lack of appropriate market mechanisms in the region (Slaughter and Wiener, 2007). Drought prone areas, such as southern Idaho's Snake River plain, have access to a number of market mechanisms in which irrigators are both buyers and sellers of irrigation water (Slaughter and Wiener, 2007). In contrast, water rights in the Klamath Basin were fully adjudicated only recently. This lack of legal framework has created fundamental obstacles for establishing water markets which could facilitate water use transfers (Burke et. al., 2004). Nevertheless, Burke, Adams, and Wallender (2004) note that despite these obstacles, water transfers for environmental purposes are increasing. With improved capability to adjudicate, monitor, and enforce water property rights, market mechanisms can facilitate water buyback programs based on direct water right idling rather than based on land idling. Such a design would reduce program costs by avoiding payments for land as factor of production and by ensuring that least valuable marginal units of water are idled before higher marginal value water units.

The advances made in data availability and computational power have allowed for incorporation of Geographical Information System (GIS) data into economic modeling. We demonstrate a straighforward method for empirically estimating the economic value of irrigation water by combining mathematical programming with soil productivity data available in most regions of the US. The advantage of our approach is that it can be readily used anywhere such data is available. Also, the method is easily adaptable for examining the effectcs of techological improvements, irrigation efficiency changes via ET, and soil productivity changes because it is based on actual agronomic crop production functions expressed in terms of per acre applied irrigation water.

Monitoring and enforcement costs associated with direct water buy-back programs are not empirically addressed in this study. Therefore, the results of this study provide only partial information needed for an informed decision about advantages of direct water buy-back programs versus land idling-based water acquisition programs. However, expected present value of the savings generated from replacing land idling based water buy backs with direct water buybacks represents resources available for investing in water use monitoring. Further, costs of monitoring and enforcing direct water buyback programs are likely to fall over time. New technologies, like NASA's new satellite imaging can replace the need for installation and maintenance of on-site water meters. Investments in water use monitoring infrastructure can generate benefits not just in terms of reducing the costs of water buyback programs but also in terms of water right monitoring, budgeting, and enforcement in general. Nevertheless, future studies ought to compare potential benefits from direct water buy-back programs to costs of implementing, monitoring, and enforcing such programs according to specific technological parameters.

This study is based on annualized production functions and water availability. Therefore, the current model is not suitable for studying timing of water availability and irrigation activities during the growing season. Timing of water availability for irrigation can affect the marginal value product of water during the growing season. In this analysis water idling decisions, whether via land or water idling, are assumed to be made at the annual time-scale, before the irrigation season. In practice farmers in this region make most planting decisions in early spring when BOR announces anticipated water availability for the irrigation season. Nevertheless, the model assumes that farmers will apply available water according to its highest marginal product during the year. The results here assume that the producers are able to cut back on water use during low marginal productivity periods and use the available water during high marginal productivity periods. This assumption can be relaxed with the development of dynamic production functions which express yield as a function of water applied in various periods throughout the growing season. Future studies should examine the timing aspects of water availability during the growing season to obtain temporally explicit marginal value product of irrigation water.

The planted crop acreage in this study is restricted to historically observed crop mix combinations. This specification constrains the model to reflect agronomic and managerial crop rotation requirements which affect planted acreage decisions. In the absence of such constrains the optimization model will over-plant more profitable crops and under plant lower value crops relative to crop mixes observed in practice. However, the limitation of this specification is that optimal crop acreages may fall outside of the historically observed ranges when land and/or water availability is set at values not observed in recent history. In this respect, the benefits of the direct water buying program relative to the land idling based program may be underestimated in this study.

The effect of climate change on snowpack could be devastating to already low surface water reserves. Snowpack is essential to surface water, especially during the dry growing summer months. Irrigators and ecosystems which rely heavily on surface water, as is the case in the Klamath Basin, could face even further reductions in water availability (Adams, 1989; Burke et. al., 2004). Hence, water conflicts such as those experienced in the Klamath Basin in 2004 and in 2010 are likely to increase in frequency. Efficient mechanisms for mitigating such water shortages, including but not limited to water buyback programs, are of high importance for policy makers and water managers.

APPENDIX

Crop production parameters

There are five parameters in the crop production function (Equation 4). These are maximum evapotranspiration at full irrigation (ETm_c), non-irrigated evapotranspiration (ETd_c), dry or non-irrigated yield ($Yd_{c,s}$), max yield at full irrigation ($Ym_{c,s}$), and maximum irrigation depth ($Im_{c,s}$). Calculations for obtaining these parameters are explained below. Although no crops in the Klamath basin are grown without irrigation, these parameters, obtained based on data from AgriMet and NRCS-Web soil survey as discussed below, are used to express yield in terms of applied water (Equation 4).

A1. Evapotranspiration at full irrigation ETm_{cr}

Evapotranspiration rates at full irrigation are taken from AgriMet historical "Evapotranspiration Totals and Averages" (http://www.usbr.gov/pn/agrimet/ETtotals.htm). Rates are available for each crop and are calculated by averaging evapotranspiration totals from weather stations KFLO, LORO, and WRDO from 1999 to 2010.

A2. Evapotranspiration at non-irrigation ETd_{cr} .

Non-irrigated, dry, evapotranspiration ETd_{cr} is calculated as

$$ETd_c = precipitation\ stored\ in\ root\ zone\ at\ planting_{c,s} + growing\ season\ precipitation_c \times precipitation\ efficiency \quad (11)$$

A2.1. Growing Season Precipitation

Growing season precipitation is the total precipitation during the growing season for each particular crop. Growing season for each crop is defined by AgriMet (http://www.usbr.gov/pn/agrimet/irrigation.html). This data was calculated by summing daily precipitation over the appropriate crop season. Daily precipitation rates used in the model are yearly averages from weather stations KFLO, WRDO, and LORO from 1999 to 2010 (http://www.usbr.gov/pn/agrimet/webarcread.html). Years for which there is no record were omitted for the purpose of averaging.

A2.2. Precipitation Stored in Root Zone at Planting

Precipitation stored in root zone at planting depends on *maximum available precipitation stored in root zone at planting* and *unlimited precipitation stored in root zone at planting*. If maximum available precipitation stored in root zone at planting exceeds the value of unlimited precipitation stored in root zone at planting, then unlimited precipitation stored in root zone at planting is used as stored precipitation in root zone at planting; otherwise, maximum available precipitation stored in root zone at planting is used.

A2.2.1. Maximum Available Precipitation Stored in Root Zone at Planting

Maximum available precipitation stored in root zone at planting is total precipitation beginning in October until the start of the following year’s growing season for each crop. This is calculated using daily precipitation and local growing season start dates defined by AgriMet. Precipitation averages from KFLO, LORO, and WRDO weather stations were taken from 1999 to 2010. Missing values were omitted for the purpose of calculating average precipitation rates.

A2.2.2. Unlimited Precipitation Stored in Root Zone at Planting

Unlimited precipitation stored in root zone at planting is determined by *crop root zone depth, average soil water holding capacity, and soil maximum root depth*. For a given soil class, if the maximum root depth allowed by the soil is greater than a particular crops root zone depth, then unlimited precipitation in root zone at planting is defined by crop root zone depth multiplied by soil average water holding capacity. If soil maximum root depth is less than a particular crop's root zone depth, then the unlimited precipitation in root zone at planting is defined as soil maximum root depth multiplied by average soil water holding capacity.

A2.2.2.1. Crop Root Zone Depth

Crop root zone depth is the soil depth from which each crop at maturity draws 90% of its moisture. Root zone depth by crop is available from AgriMet (http://www.usbr.gov/pn/agrimet/irrigation.html#Root). Peppermint root zone depth was not available through AgriMet and was instead taken from an Oregon State University extension service publication (Mitchell, 1997).

A2.2.2.2. Average Soil Water Holding Capacity

Average soil water holding capacity is the quantity of water that a particular soil type is capable of storing for use by plants. It is derived from the NRCS soil data report "Physical Soil Properties" (http://websoilsurvey.sc.egov.usda.gov/app/WebSoilSurvey.aspx). Average water holding capacity is calculated for each specific soil type using "Depth" and "Available water capacity” measured in inches. Each soil type has several depth levels with corresponding ranges of available water holding capacity. In the calculations, each soil level is divided by total soil depth and multiplied by its associated average available water capacity. These values are summed giving a final weighted average soil water holding capacity for a specific soil type.   Each “Map symbol” is comprised of several soil types but only the major soil type is considered in these calculations.

A.2.2.2.3. Soil Maximum Root Depth

Soil maximum root depth is the maximum root depth allowed by the soil of particular type and is taken from the second column of “Physical Soil Properties” report (http://websoilsurvey.sc.egov.usda.gov/app/WebSoilSurvey.aspx).

A3. Maximum Yield at Full Irrigation $\boldsymbol{Ym_{c,s}}$

Maximum yield at full irrigation is calculated using crop yields from NRCS’s Soil Data Mart and maximum crop yields reported by Oregon State University extension (B. Charlton, personal communication, July, 2010).

$$Ym_{c,s} = YeildNRCS_{\ c,s} * \frac{Ym_c}{\max_s\{YeildNRCS_{\ c,s}|c\}} \quad (14)$$

Where $YieldNRCS_{c,s}$ is per acre crop yield on a particular soil type as reported in NRCS data; Ym_c is maximum per acre crop yield obtained from OSU extension; and NRCS irrigated per acre crop yields are crop production capabilities of each soil type at the time when the survey was conducted. Current maximum potential per acre crop yields are obtained from OSU extension agents and are yields which can be attained under ideal conditions of most productive soil type, full irrigation, and ideal management practices (B. Charlton, personal communication, July 2010). NRCS reported yields can be deemed outdated and not reflective of current productivity levels. Therefore, to calculate current production potential of each crop and soil type combination, the highest reported yield by NRCS, across all soil types for a particular crop, is replaced with the maximum yield reported by OSU extension. Each crop's maximum potential yield obtained from OSU extension agents (these estimates do not vary by soil type) is divided by the highest of the maximum yields of a particular crop across all soil types reported by NRCS. The obtained coefficient is used to adjust the NRCS crop yields on the remaining soil types. This adjustment produces yield estimates for each soil type and crop, reflecting current advances in agricultural production while maintaining the relative productivity differences across soil types.

Not all crop yields grown in the Project were available in NRCS data. In those cases where crop yield was not available from NRCS data, crop rotation information was used to identify soil types on which certain crops could be grown. Productivity for missing crop types was calculated using the relative productivity of other crop types in the rotation and observed maximum yield of the missing crop as follows:

$$Ym_{-c,s} = \left(\frac{\sum_c \frac{YieldNRCS_{c,s}}{Ym_c}}{NCRot} \right) * Ym_{-c} \quad (15)$$

where, c are crops in the rotation for which there is NRCS data; $-c$ is the crop with missing information; and $NCRot$ is the number of crops in the rotation for which there is NRCS data.

A4. **Non-Irrigated Crop Yield $Yd_{c,s}$**

Non-irrigated crop yield is obtained using maximum $Ym_{c,s}$, ETm_c, and ETd_c as follows:

$$Yd_{c,s} = Ym_{c,s} * \frac{ETd_c}{ETm_c} \quad (16)$$

A5. **Irrigation depth at full irrigation $Im_{c,s}$**

Irrigation depth at full irrigation is estimated with ETm_{cr} and irrigation efficiency (Martin et. al., 1989).

$$Im_{c,s} = \frac{ETm_c}{Irrigation\ Efficiency} \quad (17)$$

Irrigation efficiency is the ratio of stored water at root zone to applied irrigation water. The two irrigation technologies considered are sprinkler and gravity which have an irrigation efficiency rate of 0.7 and 0.65, respectively.

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Table I. Estimates of Derived Demand Curves and Values of 45K AF Idled Water Under Deficit and no Deficit Irrigation Scenarios.

	With Deficit Irrigation	With No Deficit Irrigation
θ	0.082	0.663
St. Err.	(0.0173)	(0.0455)
Z-value	4.74	14.57
P-value	0	0
β_1	-9.84E-06	-0.00012
$\chi^2(1)$	830.492	474.753
P-value	0	0
β_0	7.904	77.92
	Value of idled irrigation water	
MVP^{low}_{x*}	6,601,133	11,300,000
Std. Err	(1,246,787)	(3,139,579)
P-value	0.013	0.037
MVP^{med}_{x*}	1,782,845	5,512,179
Std. Err	(189,715)	(1,272,237)
P-value	0.003	0.023
MVP^{high}_{x*}	779,404	2,866,820
Std. Err	(51,003)	(540,234)
P-value	0.01	0.013

Table II. Estimates of Land MVP Curves and Values of Enough Idled Land to Reduce Surface Water Deliveries by 45k AF under Deficit and no Deficit Irrigation Scenarios.

	With Deficit Irrigation	With No Deficit Irrigation
θ	0.814	0.799
St. Err.	(0.0449)	(0.0464)
Z-value	18.11	17.2
P-value	0	0
β_1	-0.002	-0.001865
$\chi^2(1)$	524.300	518.075
P-value	0	0
β_0	400.000	364.7423
	Value of idled land	
MVP^{low}_{x*}	10,800,000	12,000,000
Std. Err	(3,229,005)	(3,813,918)
P-value	0.044	0.051
$MVPmed_{x*}$	5,411,186	6,141,266
Std. Err	(1,415,205)	(1,751,986)
P-value	0.031	0.039
$MVPhigh_{x*}$	2,368,776	3,340,231
Std. Err	(513,569)	(853,158)
P-value	0.019	0.03

Figure I. Klamath Irrigation Project and Soil Types

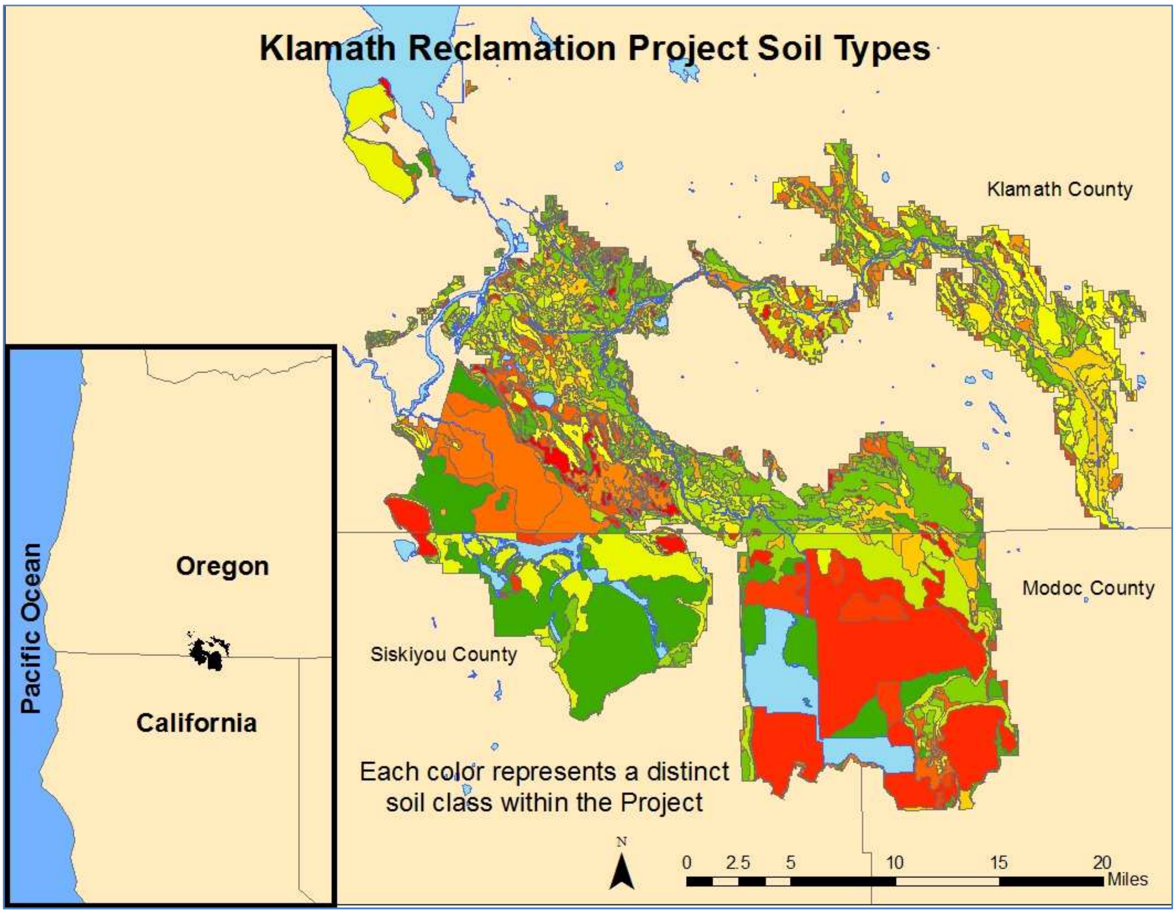

Figure II. Theoretical Illustration

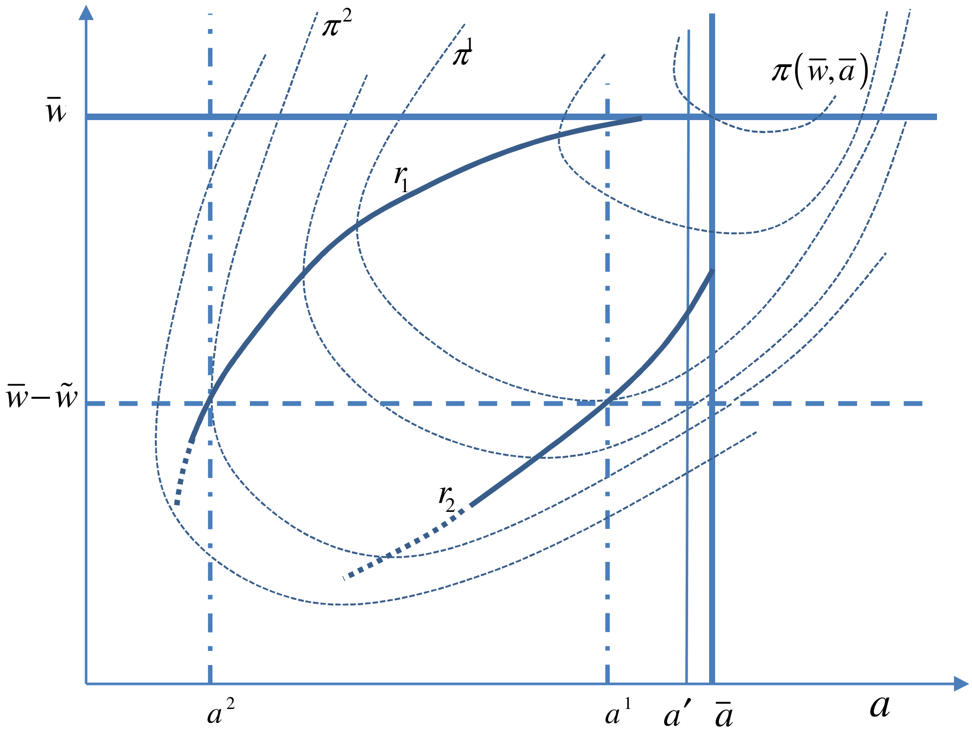

Figure III. Production Function Summary

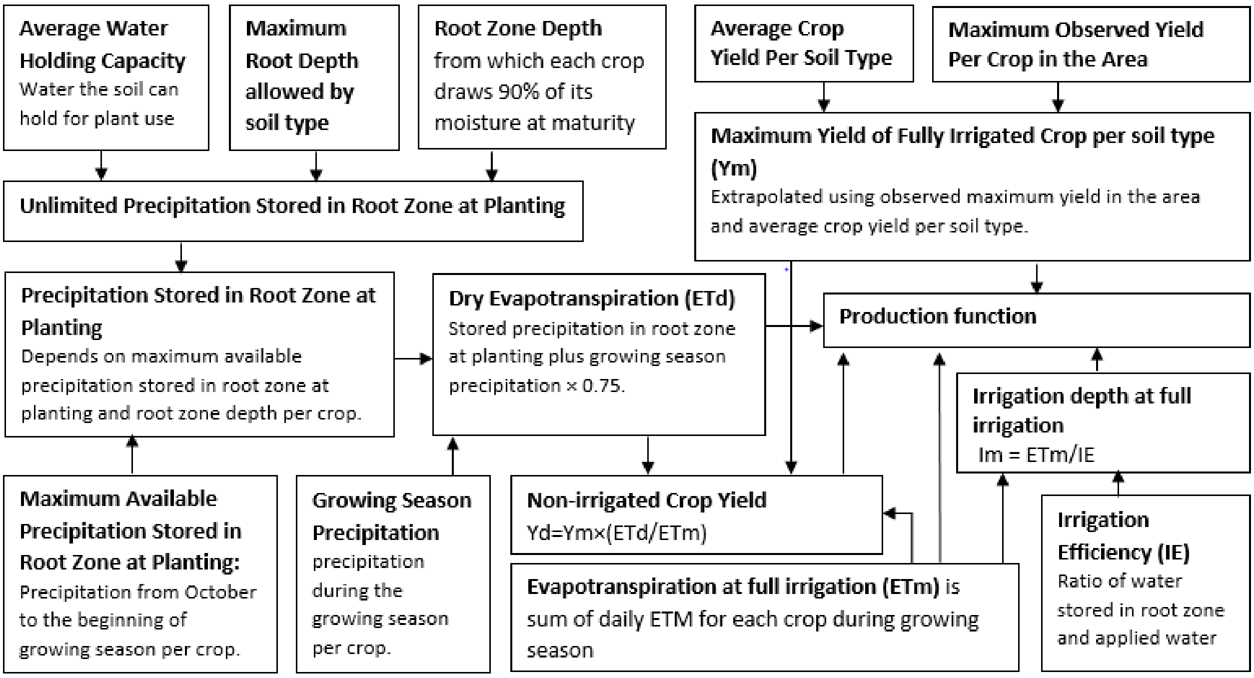

Figure IVa. Demand with Deficit Irrigation

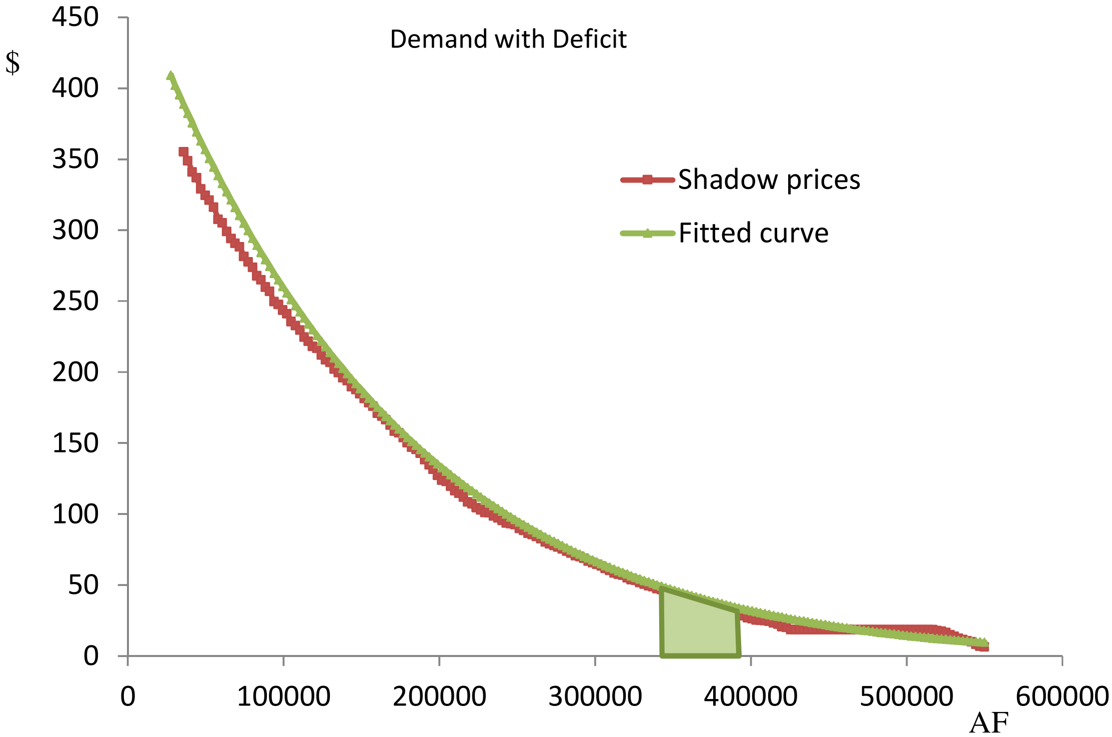

Figure IVb. Demand without Deficit Irrigation

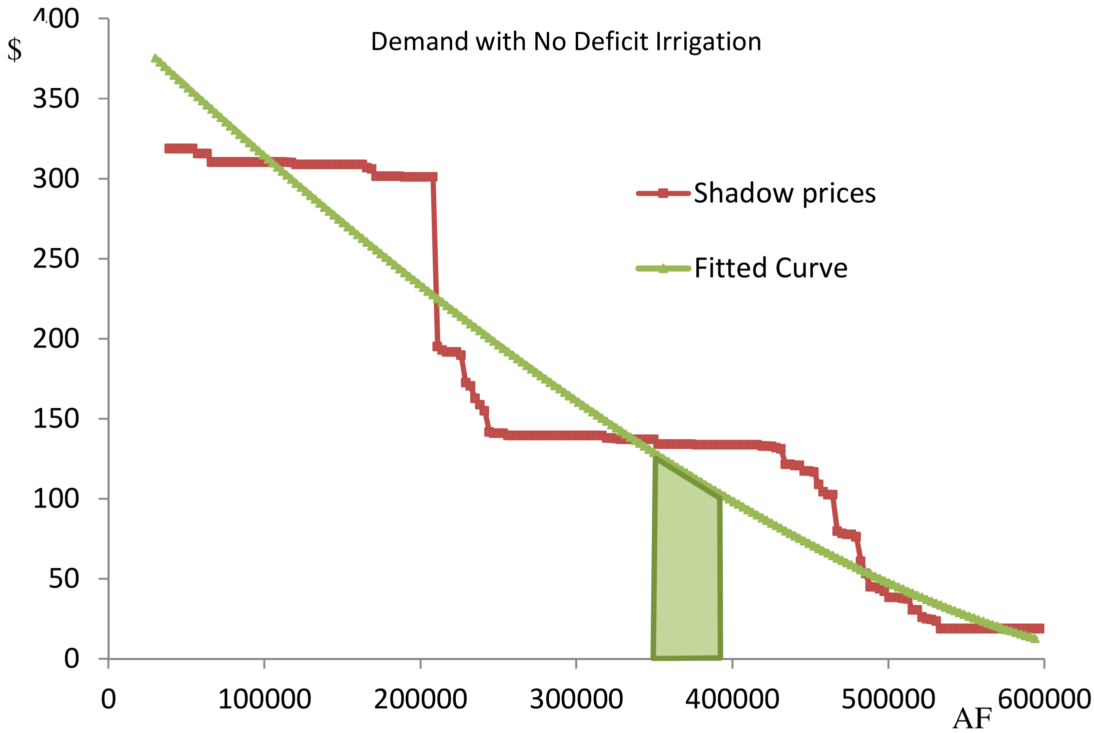

Table A1. Model Validation.

	Observed			Simulated		
	min	average	max	Ground	Surface	Total
			Oregon			
Pasture	37,870	41,408	43,304	6,570	34,461	41,031
Alfalfa	38,510	42,051	45,044	8,849	32,636	41,485
Oats	1,579	2,428	2,842	395	2,447	2,842
Barley	3,887	6,367	7,994	1,983	6,011	7,994
Wheat	5,075	9,184	13,740	1,368	3,707	5,075
Hay	12,782	14,664	17,286	3,524	12,965	16,489
Potatoes	2,634	3,678	4,339	494	3,845	4,339
Peppermint	78	212	348	348		348
Onions	-	289	509		509	509
			California			
Pasture	1,502	1,785	2,176	32	1,817	1,849
Alfalfa	16,687	19,593	20,820	1,133	19,001	20,134
Oats	116	571	1,100		492	492
Barley	5,958	7,010	8,641		5,958	5,958
Wheat	16,029	18,166	19,873	22	19,066	19,088
Hay	2,479	3,140	3,746		2,479	2,479
Potatoes	7,408	8,461	11,100		11,100	11,100
Peppermint	2,115	2,597	3,122		2,574	2,574
Onions	2,135	2,789	3,297		2,730	2,730

[i] The use of the term “idle” in this paper should not be interpreted with a negative connotation of underutilized resource. We use the term “idle” to only reflect non-use of water and/or land in agricultural production. Benefits from land and water idling in terms of improvements to environmental quality are recognized.

[ii] Some technological progress has been made in remote sensing of consumptive water use. See for example Allen et al. (2007).

[iii] The assumption of 2 to 2.5 acres was taken from a combination of average water holding capacity of Project soil and crop root zone depths. This range of values also coincides with the USGS 2001 and 2005 reports of the estimated water use (Hutson et. al., 2004; Kenny et. al., 2009).

[iv] Pseudo scale lines connect all points of profit maximization for one input assuming other input(s) are held constant. The concept is analogous to ridgelines in technological production functions. Unlike ridgelines which expressed output in terms of input, pseudo scale lines express profit in terms of input and are applied to isoprofit contours rather than isoquants.

[v] It is straightforward to see that for isoprofit topography with no pseudo scale lines, no reduction in water use will be attained by reducing acreage in production.

[vi] While most crops grown in the study area are not produced without irrigation this parameter can be obtained using available estimates of maximum yield, ET corresponding to maximum yield, and ET corresponding to no irrigation.

[vii] The Groundwater Pumping Program aids irrigators in securing groundwater to supplement surface water irrigation. Irrigators who qualify for the program enjoy subsidized rates to offset the cost of groundwater pumping (Lewis et al., 2004). The 2001 irrigation curtailment led to a number of new wells which increased pumping capacity between an estimated 75,000

(Braunsworth et al., 2002) to 95,000 AF (USGS, 2005). Continued well construction has increased the groundwater pumping capacity within the Project to an approximate range between 200,000 and 250,000 AF (Klamath Water Users Association [KWUA], 2010).

[viii] Non-irrigation related variable costs of production are obtained by subtracting all water-related costs from variable costs in crop budget reports.

[ix] Surface water irrigators face per acre operation and maintainence (O&M) charges regardless of the amount of water used. O&M charges vary among irrigation districts, ranging from $12 to $70 an acre. We use a weighted average O&M fee from the five largest irrigation districts within the Project. The irrigation districts include the Klamath, Tulake, Klamath Drainage, Horsefly, and Langel Valley districts which provide over 80% of irrigation water to agricultural acres within the Project. In addition to O&M charges, irrigators of onions and potatoes also incur costs for sprinkler equipment rental. Most irrigators of onions and potatoes do not purchase the sprinkling system required for these crops and instead choose to rent the equipment (R. Wilson, UC Davis Extension, pers. comm. 2011). Based on crop budget reports, these costs are $159 and $170 per acre for potato and onion production respectively, in 2010 dollars.

[x] Pumping water charges come from the Klamath Water and Power Authority (KWAPA). In 2010, the KWAPA facilitated pumping of over 100,000 AF to supplement Project surface irrigation (H. Cannon, personal communication, April 2010). While this is not a complete account of groundwater pumping that occurs in the Project, it does represent approximately half of the groundwater used in 2010 (KWUA, 2010). KWAPA charges $10 per acre foot of groundwater irrigation and associated pumping costs which vary per state. Oregon irrigators paid $8.62 and California irrigators paid $20.27 per acre foot in 2010.

[xi] AgriMet is a network of agricultural weather stations operated and maintained by the U.S. Bureau of Reclamation. The stations are located in irrigated agricultural areas throughout the Pacific Northwest.

[xii] http://www.water.ca.gov/landwateruse/lusrvymain.cfm

[xiii] http://www.oregon.gov/OWRD/MAPS/index.shtml#Water_Right_Data_GIS_Themes

[xiv] Oregon groundwater use is heavily regulated. Oregon GIS data contains specific information on where groundwater may be utilized (e.g., point of diversion and use). Unlike Oregon, California groundwater is less regulated. The California GIS data contains only partial information on groundwater source and use. The available data was utilized and included in the model, though it is recognized that this data underestimates the acres in California which could be irrigated by groundwater.

[xv] Klamath project operation plan in 2010 included 150,000 AF of surface water deliveries. (USBOR, 2010a). Therefore, we use 200,000 AF as a point of reference.