THESIS

WATER REPLENISHMENT THROUGH AGRICULTURAL WATER CONSERVATION:

AN ECONOMIC ANALYSIS OF DEFICIT IRRIGATION

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ABSTRACT

WATER REPLENISHMENT THROUGH AGRICULTURAL WATER CONSERVATION: AN ECONOMIC ANALYSIS OF DEFICIT IRRIGATION

Available freshwater supplies are under growing pressure due to climate variability and expanding development. Water-intensive companies are becoming increasingly aware of the importance of managing their water use due to the impact it has, both on corporate profitability and local ecosystems. Many corporations have calculated the water footprint of their products to determine where reductions might be made.

Water neutrality is an extension of a water footprint audit, and involves a consumer or producer reducing their water use as much as possible and then using additional measures to offset any remaining water use. Those additional measures include working with other water users to reduce their water use. For instance, a third party could contract with an agricultural producer and pay them reduce their own water use and then lease a portion of their water right.

The objective of this thesis is to determine whether agricultural water conservation can be used to offset a business's residual water use, and more specifically, whether deficit irrigation can be a profit-maximizing option for that conservation. To that end, an optimization model was created and run in Excel's Solver using data from a USDA deficit irrigation research farm to estimate crop water production functions. The results of the model illustrate a range of

profit maximizing crop mixtures and indicate potential lease quantities given a range of crop prices and lease payments.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

Water is an increasingly scarce resource with many competing uses. As the likelihood of negative consequences of scarce, vulnerable water supplies becomes more apparent, corporations such as MillerCoors, Coca-Cola, and IBM are monitoring their water consumption to better understand the water footprint of their products and determine where reductions might be made.

A water footprint represents the total volume of water that is consumed in the production of goods and services (Hoekstra, 2008). Conducting a water footprint audit allows a consumer or producer to calculate cumulative water use, typically with the goal of reducing the total amount of water consumed. A much newer concept, water neutrality, takes this approach one step further. Consumers or corporations can become water neutral by first reducing their consumptive water use, as often follows a water footprint calculation, and then finding ways to offset any residual water consumption that still exists. Water is “consumed” or “consumptively used” if it is lost to the atmosphere during the production of some good or service. An example of this is the water lost through the evaporation and transpiration processes during crop growth, known collectively as evapotranspiration (ET).

Once opportunities for water reductions have been identified and met, offsetting residual consumptive water use can be achieved through investing in local water projects or working with other water users in the same watershed to reduce their water consumption. If a company is successful at becoming water neutral then, all other things remaining constant, the result will be either increased instream flow rates or a decrease in the amount of groundwater pumped. However, this result is dependent on local hydrology and it should be noted that withdrawal and replenishment rarely occur simultaneously; this can mean that the additional water is not available when expected or needed.

In Colorado, where water supplies are over-appropriated, and the development of "new" water is cost-prohibitive, reallocation from agricultural uses to other sectors is often desirable. Transfers between the agricultural sector and municipal or industrial uses often involve the "buy and dry" approach, in which previously irrigated land is fallowed and the water used there is transferred to other uses. A possible alternative to this method is the use of deficit irrigation (DI), an irrigation technique in which farmers use less than their full water right for irrigating, by applying water at below crop requirements.

The use of DI may allow farmers to lease a percentage of their water right to a corporation while maintaining farm revenues. For businesses working toward water neutrality, offsetting their residual water use by leasing from DI farmers can fulfill the offset requirement without taking farmland out of production. This approach does of course require the participation of significantly more farmland to conserve the same amount of water when compared to the "buy and dry" alternative approach, but with fewer potentially negative effects to rural farming communities.

The objective of this thesis is to determine whether agricultural water conservation can be used to offset a business's residual water use, and more specifically, whether deficit irrigation can be a profit maximizing option for that conservation. The water neutral program is still evolving, and the use of DI as an irrigation technique is relatively new, meaning that there is little research available that combines the two concepts.

In order to evaluate the suitability of DI as a method for offsetting residual water use, the following steps were taken in this thesis:

(1) An economic analysis of the production and profit functions of corn, winter wheat, dry beans, and sunflowers (oil) was conducted to determine the likelihood of a DI crop being a profit-maximizing crop choice

(2) A farm-level model specific to Weld County, Colorado was created to determine profits under various levels of DI for each of the four crops

(3) The model was solved using Excel's Solver Optimization, and multiple iterations were run, to calculate maximum profits when water is allocated to a combination of crop growth and leasing

(4) The results of the optimization were interpreted through a series of graphs and tables in order to compare the outcomes given different crop prices and lease payments

(5) A sensitivity analysis was completed to ensure robust solutions

There are some necessary conditions that must be met when considering the use of DI and its contribution to water neutrality. Certain assumptions are made in this thesis without which DI would likely not be a potential candidate for offsetting water use. This thesis assumes that the costs associated with implementing DI and monitoring actual consumptive water use are low. To the extent that this is not the case, the results here will overstate the potential of DI in that high costs would make it less likely for a third party to initiate this type of leasing agreement. This thesis also assumes that there will be no long-term effects to a farmer's water right after participating in a lease agreement as, under Colorado Water law, that water right is determined by historic beneficial use.

As there is currently no data from field trials that are specific to this thesis, the farm-level model makes use of data from a USDA DI research farm to determine the suitability to deficit irrigation of four common Northern Colorado crops: corn, winter wheat, sunflowers (oil), and dry beans. This thesis will use the data from these crops, along with crop price data and potential lease prices, to examine the following:

- The optimal combination of crops and leasing for a representative farm
- The amount of conserved water that can reasonably be expected from that farm
- The cost to the business of that conserved water.
- The robustness of the optimal solution given changing prices and costs

The model determines the optimal amount of water to be allocated to irrigating crops and the optimal amount leased to a business, based on crop prices and a range of leasing payments. The results of the model will establish the optimal economic returns from a combination of water leasing and crop growth and will illustrate the amount of total water conservation that could reasonably be achieved by the representative farm. This thesis is not intended as a management plan for the technique of DI, but rather as a guide in determining the amount of water conservation possible given certain conditions, and to assess whether it is a suitable technique for achieving reliable water conservation.

These results will be useful in guiding both agricultural producers, in their decision of whether or not to participate in a leasing agreement, companies, in understanding the value of irrigation water in their region, and policy makers interested in promoting DI as an alternative to permanent water transfers. This information is also useful for other entities interested in entering into water-leasing agreements and any stakeholders or researchers interested in the use of optimization models for determining the optimal allocation of resources. Additionally, this research contributes to the agricultural economics literature by further describing the value of water in agriculture.

The remainder of this thesis is organized in the following chapters: “Background” includes an example of a firm interested in contracting with farmers as part of their goal to become water neutral. It also further defines water neutrality, deficit irrigation, and water use in Colorado specifically. The “Literature Review” discusses previous work with optimization models and the research available in the areas of deficit irrigation, water neutrality, and transferring water from the agricultural sector to instream flows. The “Analytical Framework” details the equation that the model is based on. The “Methodology” section examines the crop production functions and describes the model and data. The “Results and Analysis” section describes the outcomes from three different model scenarios, why they occur, and how they apply to participants in a leasing agreement. Lastly, “Conclusions, Limitations, and Future Research” recaps the final results, examines any omissions or oversights in this thesis and suggests topics for future work.

CHAPTER 2: BACKGROUND

As an example of the previously mentioned water offset strategy, Coca-Cola and Colorado State University (CSU) have partnered together on a water replenishment project in Northern Colorado. This collaboration is part of Coca-Cola's Community Water Partnerships, which boasts 386 projects in 94 countries, with over one-third of those designated as Watershed Protection projects. The CSU – Coca-Cola project focuses on the South Platte River Basin, in which Coke's Denver bottling plant is located. Coca-Cola's goal is to increase stream flow in the South Platte River by replenishing the 50 million gallons, equal to 154 acre-feet, which are withdrawn by their bottling plant each year. They are undertaking this as part of their bigger goal to be water-neutral as a company by 2020, which can be achieved by replenishing all of the water used in the production of their finished beverages.

Coca-Cola estimates that as of 2012 they had replenished approximately 52 percent of the water that was used in their finished products by establishing locally relevant water replenishment projects worldwide. They will reach their goal of water neutrality by reducing their water footprint at each location and then working to offset any residual water use that has not been reduced. The standards of water footprint accounting and water neutrality are relatively new and are still being developed (Hoekstra, 2008). For that reason Coke is working with The Water Footprint Network and The Nature Conservancy to better articulate the steps necessary to properly perform a water footprint analysis and the standards that must be followed in order to achieve water neutrality.

Motivated by the goal of becoming water neutral, Coca-Cola is interested in partnering with farmers who are willing to reduce their on-farm water use and lease a portion of their water right to Coke in order to increase in-stream flow rates in the South Platte River. Their project will make use of existing farmland, infrastructure, and monitoring equipment that is owned by Parker Water and Sanitation District, located in Logan County in the northeastern part of the state. That land is currently leased to farmers that CSU has worked successfully with in the past.

In contrast to typical water leasing agreements that look at water transfers between the agricultural sector and municipal or industrial uses, this thesis focuses on reducing agricultural water use in order to reduce withdrawals from the South Platte River. Coca-Cola is interested in evaluating different methods for conserving agricultural water and one option is to work with producers who are interested in using DI. Part of the strategy of DI is to identify crops for which the reduction in crop yield is proportionally less than the reduction in the amount of water used. As Fereres and Soriano (2007) point out, when yield decrease is proportionally less than the decrease in ET, the productivity of water increases.

Adapting their irrigation techniques in response to a decrease in available water supplies allows producers to participate in the leasing program but it also creates farms that are more resilient to drought. Moreover, this is a preferred alternative to the previously mentioned "buy and dry" approach of permanently transferring the entire water right to another user because farmers are able to maximize profits while maintaining a productive farm.

Water Neutrality

The concept of water neutrality originated from Pancho Ndebele during the 2002 Johannesburg World Summit for Sustainable Development (Hoekstra, 2008). Participants of the 10-day summit were encouraged to calculate their water footprint to determine the amount of water that they used while in South Africa, and purchase water-neutral certificates to offset their total water consumption. That money was then invested in local water projects such as improving access to fresh water supplies.

Following collaboration between Ndebele and the creator of the Water Footprint concept, Arjen Hoekstra, visitors to South Africa can now easily calculate and offset their water use through the use of those certificates. However, the costs associated with monitoring consumptive use and replenishment are often high, so that scaling the same concept for use by corporations and larger groups is more difficult.

As the concept is currently defined, to become water neutral, water users must first conduct a water footprint assessment. Next, users take all “reasonable measures” to reduce consumptive water use. This would include using available water saving technology and implementing wastewater treatment methods. The second step is to offset any residual water use by making “reasonable investments” in local water projects or contracting with other water users. As previously mentioned, the guidelines for achieving water neutrality are somewhat poorly defined. Coca-Cola is working with The Nature Conservancy and Arjen Hoekstra’s Water Footprint Network in order to more clearly outline the steps necessary for companies to achieve water neutrality.

Colorado Water Law

Water rights in Colorado are governed under a prior appropriation, or "first in time, first in right", system of water allocation. When this system was established, an interested party needed only to divert water from a river or stream and then apply it to a beneficial use (Jones and Cech, 2009). The water right could be used in areas far from its source, or sold to other parties, and earlier diversions were afforded more senior rights with higher priority to available water. This is different from riparian water law, a system in which the water right is directly attached to the property that adjoins the water source.

Today, most available sources of water have already been developed and parties interested in obtaining new water rights are more likely to purchase or lease them from existing owners. The specific laws that govern how that water can be transferred are crucial for participants in a leasing agreement because they determine how much water can be transferred, and when.

In the particular case in this thesis, in which a business is potentially transferring water away from a farmer in order to offset their own residual water use, two features of Colorado water law are critical. First, the law allows water to be transferred away from the farm without affecting the farmer's land holdings. Second, in both temporary and permanent water transfers, water rights owners are able to transfer their water only if they can prove that any transfer will not be injurious to other users within the basin. This means that they can only transfer water that historically has been consumptively used on their land. For the business in the leasing agreement, this distinction is important because it determines the amount of water they can anticipate receiving from a farm.

The Water Cycle in Agriculture

Water applied in irrigated agriculture is either lost to the atmosphere through evaporation from soil and the transpiration process of crops, or it stays within the river basin. Traditionally, crops are given enough water to ensure that they transpire at the maximum amount and that full evapotranspiration (ET) requirements are met (Fereres and Soriano, 2007). Without precise application techniques this typically means that crops receive more water than necessary in order to meet those requirements. The excess water that is not used in the evapotranspiration process either percolates into the soil, replenishing soil moisture and groundwater supplies, or it is surface runoff, making its way back to the original water source to be used downstream.

In Colorado, for an irrigation technique to conserve water that can then be leased to other users, there must be a decrease in the amount of water that has been consumptively used. There must be less water lost through ET. Applying less water without decreasing the amount of ET only means that the amount of water available to downstream users has decreased. Previous efforts in reducing agricultural water use through the adoption of more efficient application techniques have resulted in improved water placement and crop growth, but have decreased the return flows back to the river basin, negatively effecting downstream users (Ward and Pulido-Velazquez, 2008). For this reason, the focus of this study will be the relationship between crop yield and the amount of water consumptively used (ET).

The Water Balance approach is a common way for irrigators or researchers to quantify the ET from a crop, and then calculate the potential for conserving water based on that total. The Water Balance equation is the mathematical form of the guidelines described above

(2.1) Precipitation + Irrigation = ET + Runoff + Deep Percolation + Change in Soil Moisture

Under Colorado water law, ET is the only component that the farmer “owns”, in the sense that they have the right to put it to beneficial use, and thus the only part that can be transferred. Any changes made to the irrigation technique or amount of water applied can only be undertaken if there is no change to return flows and thus to the amount of water available to other users. A third party leaser would need to ensure that historical flows are maintained in volume, timing, and location. (Colorado Agricultural Water Alliance brochure, 2009). For this reason, ET is the measurement of interest in the model when determining the amount of water available to lease.

Deficit Irrigation

Deficit irrigation is a technique in which water is applied primarily during drought-sensitive stages of crop growth, with less than the full water requirement applied at other stages. The results vary widely across crop types but often the percent reduction in crop yield is less than the percent reduction in irrigation. This is due to an increase in water use efficiency (WUE); how well a crop uses an additional unit of water. WUE is the ratio of marketable yield to the amount of water consumptively used by the crop (ET) (Geerts and Raes, 2009). WUE tends to decline as a crop approaches full irrigation, meaning that the crop is less efficient at turning an additional unit of water into increased yield.

One of the objectives of using DI, from a farm management perspective, is to find the level of irrigation that maximizes WUE. This takes special knowledge of individual crop cycles and irrigation needs, and thus cannot be generalized across all crop types. As previously mentioned, utilizing this technique takes participation from more irrigated acres in order to reach a given water volume target over the alternative "buy and dry" scenario, but it also allows, ceteris paribus, the continuation of farming in rural communities that may otherwise be negatively affected by a decrease in farming revenues.

This thesis looks at whether DI is an effective method for reliable water conservation, as part of assessing its potential contribution to a water neutral program. This is achieved by observing the amount of water consumptively used by DI crops in the model to determine the amount of water that could realistically be transferred to a third party. This is done while keeping in mind the aforementioned goals of water neutrality and the necessary guidelines of Colorado's water laws. The following chapter discusses the current literature in regard to the use of DI and the success of one water neutral scheme in offsetting consumptive water use.

CHAPTER 3: LITERATURE REVIEW

The overall objective of this study is to create an optimization model that determines the optimal amount of water allocated to different levels of deficit irrigated crops and the optimal amount of water, if any, which should then be leased to a third party. The goal for that third party is to achieve water neutrality through the reduction of their consumptive water use, followed by a collaborative effort with other water users, such as farmers, to offset their residual use. As such, the following literature review will discuss the previous research in using optimization models for managing limited water supplies, as well as the process of becoming water neutral, the technique of deficit irrigation, and examples of water transfers between the agricultural sector and the environment.

Water Neutrality

As the concept of water neutrality develops, and more firms seek to become water neutral, it will be increasingly important to understand the ways in which it can effectively be achieved. The results of this thesis will indicate whether deficit irrigation could be part of a program to reduce agricultural water use, given specific crops and growing conditions, in order for a third party to achieve water neutrality.

The research surrounding water neutrality is sparse and the available literature consists primarily of publications by Arjen Hoekstra, a professor of water management at the University of Twente, Netherlands and a member of United Nations Educational, Scientific, and Cultural Organization (UNESCO). Hoekstra introduced the water footprint concept in 2002 and is a cofounder of The Water Footprint Network, the organization that Coca-Cola, among other firms, is working with to clarify the criterion of water neutrality and ensure there is uniformity in measuring the success of those working toward that goal.

As Hoekstra (2008) points out, the weakness of the water neutral concept in its current state is that it can too easily be used in multiple situations, affecting its ability to bring about change. In the absence of stringent guidelines, it is difficult to create a consensus on the success and effectiveness of water neutrality. The issues that need to be addressed include defining the proper measurement technique of water-conserving practices, setting an appropriate water-offset price, and discussing any temporal or spatial issues that arise given the nature of water use. One of the goals of this study is to contribute to the conversation surrounding water neutrality by providing an example that illustrates the possibilities of such a program, even if the standards and requirements are still being modified.

An example of this is the initial success of a water neutral market in South Africa. Nel et al. (2009) introduce the South African Water Neutral Scheme, a partnership between World Wildlife Fund South Africa, the South African government, research institutions, and the private sector. While the wording they use, “Review”, “Reduce”, “Replenish”, is slightly different from the terms used by the Water Footprint Network, the process and implementation are very similar. An entity interested in becoming water neutral first undertakes an audit to measure water usage, then implements a water reduction strategy, and finally invests in projects that make water available to freshwater ecosystems in an amount equal to the “water deficit” that was determined in the two initial stages.

The “Replenish” step, in which water users are required to make “new” water available, focuses on the removal of invasive and water-intensive trees and plants. The South African Water Neutral Scheme makes use of a water neutral calculator to determine the investment needed to offset a particular organization’s remaining water use. The calculator takes into account the average amount of water replenished through the clearing of a hectare of invasive plants and the total cost of clearing and maintaining that land. This information is then used to create a strategy based on how aggressively the water user wishes to offset their use to achieve water neutrality.

Based on the research done on the subject as part of this thesis, it seems that the authors are correct in stating that their study “represents one of the first examples of a water neutral scheme that quantitatively balances a water user’s accounts through investments in both demand- and supply-side management.” The authors approach illustrates an example of offsetting water use by investing in water-related projects. This thesis will provide an example of offsetting water use under the alternative option, coordinating with other water users to reduce consumptive use within the same river basin.

Agriculture to Instream Flow Transfers

Maintaining instream or environmental flow rates is a relatively new challenge when allocating water within a river basin. When Colorado’s system of water rights was being established, the principal focus was on economic development, not on maintaining habitat for fish and wildlife. Since it is not an actual diversion, water flow for environmental or recreational purposes was not even recognized as one of the beneficial uses that a water right holder was required to designate (Jones and Cech, 2009). Since that time, there has been increased interest in improving and maintaining minimum stream flows to ensure adequate water for recreational and environmental purposes.

The Colorado Water Conservation Board has an instream flow program with the specific goal of acquiring water rights to maintain lake and river water levels. Loomis (2012), Shafroth et al. (2010), and Colby (1990) have all discussed the importance of maintaining instream flows and the economic benefits attached to protecting flow rates. Now that the goal of maintaining stream flow has been identified, and Colorado's river systems are over utilized, it is necessary to identify potential sources of existing water rights to ensure minimum flow rates.

Most of the literature on water markets and water transfers centers around moving water from the agricultural sector to urban or industrial consumers. Part of the focus of this thesis is to look at transferring water from agricultural uses to instream flow. This issue will see increased interest as more areas in the western United States come up against fully appropriated river systems. Areas that are not able to maintain minimum instream flow levels risk decreased water quality, increased water temperatures, and less availability of recreational activities.

In response to this issue, Turner and Perry (1997) conducted a case study of water transfers from the agricultural sector to the Deschutes River in Oregon. The authors looked at the two most prominent irrigation districts in the Deschutes basin, the North Unit Irrigation District (NUID) and the Central Oregon Irrigation District (COID), and compared potential short-term and long-term water lease totals given three different irrigation scenarios. They used a stochastic programming with recourse model to determine how much water could potentially be diverted from agriculture given different market prices, which of the two districts would be a better source of that water, and the options that farmers have to reduce their consumptive water use in order to participate in the water market.

Their model was first run under the assumption that water had no value other than that of producing crops. It was then re-run using that value as the starting point and increasing the price of water by $5 per acre-foot until it reached $225 per acre-foot. COID land produces lower valued crops and has more senior water rights than NUID land. Although the results are from a different state and are not recent, it is still interesting to note that the authors found that for all long-term leases, COID land would be fallowed and all of the water leased at $75 per acre-foot. For NUID land, no water would be leased at less than $60 per acre-foot. The COID land is afforded more water but receives less economic return on that water. Because of this, the opportunity cost of that water is lower than that of the NUID land and, theoretically, water rights owners would be willing to lease their water for a lower price.

A comparable scenario will be further explained in the results section of this thesis. The relationship between corn and wheat is similar to that of the crops grown in the COID and NUID land, in that water is more valuable when applied to corn than it is when applied to wheat.

Nikouei et al (2012) conducted a similar study, this one looking at promoting water conservation measures on farms in the Zayandeh-Rud River Basin in central Iran. Here, the authors examined different policy options to stimulate irrigators' use of water saving technologies and increase the amount of water available to wetlands habitat.

Specifically, the study's focus is on improving water flow to the Gavkhouni Wetlands at the terminus of the Zayandeh-Rud River. The authors analyzed the effect of two potential water scenarios, a normal rainfall year and a drought year, combined with three different policy options. Those options included a base policy, which continued the status quo of water diversions in the basin and offered a 50% subsidy for the implementation of water saving measures, and two policies that enacted a water conservation requirement for the wetlands, both with and without an additional 50% subsidy to farmers who implemented water saving technologies.

The study found that both of the water conservation policies increased flows to the wetlands area in the normal and drought scenarios but return flows were also affected. Given identical climate scenarios, the increase was the same for both of the new policies when compared with the base policy. The additional 50% subsidy offered farmers greater incentive to shift out of flood irrigation and without the subsidy farmers were more likely to draw down aquifer stocks. Even though the environmental flows increased at the same rate under either policy, the one with the additional subsidy is preferred because total water use in the basin dropped considerably due to less water being pulled from the aquifer. In this case the example is instructive but it should be noted that the water laws are different in Iran, where irrigation priority comes after urban, commercial, and industrial consumers. Monitoring equipment will be used in the current study to ensure that return flows are not affected and that any changes in water use comply with Colorado water law.

Deficit Irrigation

Typically, the technique of DI could be considered successful, in regard to water conservation, if its adoption results in decreased ET, the part of applied water that can be conserved and leased, and increased WUE, with yield decline at rates lower than ET decline. Increased WUE indicates that the crop is more effective at turning additional water into crop growth relative to full irrigation. A slower yield decline is desirable because if crop yield declines at the same rate, or faster, than ET it indicates a drought-sensitive crop for which there is likely no economic benefit to deficit irrigating. However, the previous literature does not take into account a lease payment when making these determinations. If the farmer is compensated at or above the profits lost through deficit irrigating, then DI could be an option for conserving water. With that in mind, the following review of the applicability of DI does not include a discussion on compensation through lease payment.

As discussed by Geerts and Raes (2009), for some crops the slope of the WUE curve decreases as full ET requirements are reached so that the proportional yield increase per unit of ET starts to level off. Figure 3.1 below is a graph depicting an example of WUE that decreases as full ET requirements of 19.1 inches per acre are met. This crop water production function for wheat was estimated by plotting the USDA yield and ET data from 2010 and fitting a trendline to that data.

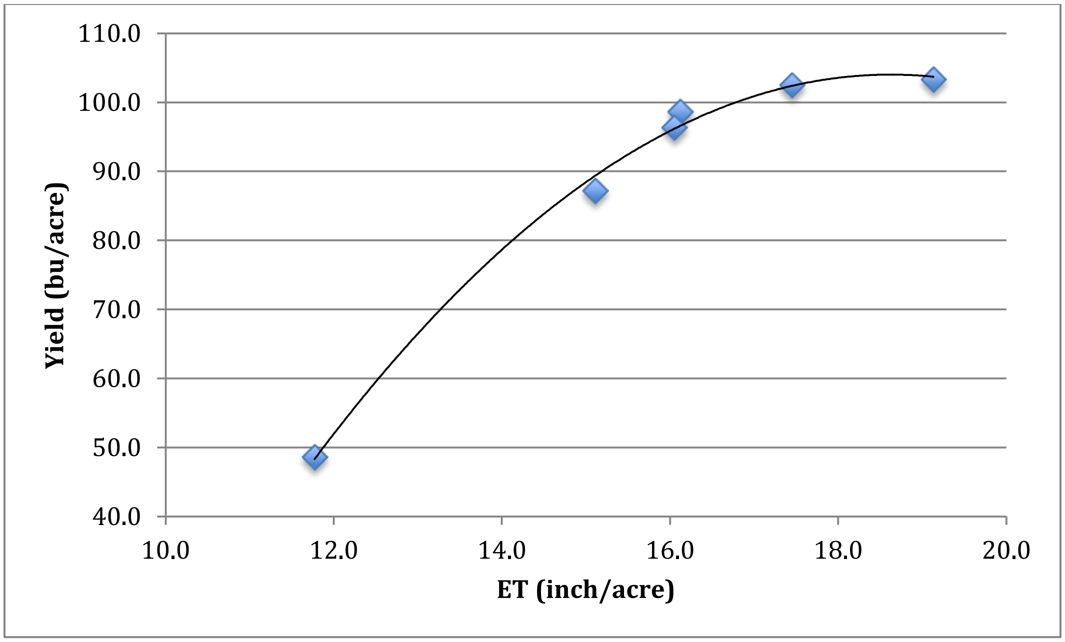

Figure 3.1: Crop water production function: wheat 2010, Greeley, CO (USDA)

Previous studies on the effect of DI on corn (Geerts and Raes, 2009), including the results from the corn grown on the USDA research farm (Trout et al, 2010), indicate that there is a linear relationship between yield and ET for that crop. This means that corn is equally efficient at using each additional unit of water, so that the marginal productivity of water is constant. In a later section, this thesis will include fixed and variable costs as part of a more complete economic evaluation of deficit-irrigated crops. If variable costs are high, and profit is maximized prior to full irrigation, then there could be an economic benefit to deficit irrigating a crop.

While corn may not be a good candidate for DI, other studies have determined that for certain crops DI can result in increased WUE without significant reductions in yield. Geerts and Raes (2009) reviewed the current research on using DI to maximize the productivity per unit of irrigation water. The authors found that several crops, including wheat and quinoa, respond favorably to DI resulting in increased WUE without drastic yield reductions.

In another study, Karam et al (2007) looked at the seed yield and water use efficiency of deficit irrigated sunflowers. Four separate replications were planted; one control crop and three others that were deficit irrigated at different growth stages. The crops were irrigated as usual during the initial establishment and vegetative stages. The authors found that when the crops were deficit irrigated starting in the earlier flowering stages, as in two of the DI treatments, seed yield and amount decreased at roughly the same rate as ET when compared to the control crop. When deficit irrigation began at the later seed formation stage though, there was no appreciable change in yield or in the amount of seed produced even though ET decreased by an average of nine percent. This indicates that with proper management techniques, DI could be used on sunflowers to conserve consumptive water use.

Webber et al (2006) studied the effects of DI on the WUE of common bean and green gram, or mung bean, in Central Asia. The crops were grown in two consecutive years using conventional and alternate furrow irrigation and treated to three different levels of irrigation: full, moderate deficit, and severe deficit. The authors found that green gram responded well to deficit irrigation, with an increase in yields for both deficit levels even given the reduction in water consumed. They did not get the same results for the WUE of common bean; here it remained fairly constant across the different irrigation treatments, indicating that it is not a likely candidate for deficit irrigation.

Similar to the previous studies, this thesis will analyze the relationship between ET and yield to better understand the effect that DI might have on the WUE of corn, winter wheat, sunflowers, and dry beans. An optimization model will then be used to determine the profit maximizing level of DI for each crop, taking into account the leasing option.

Optimization Model

In general, an optimization model is used to determine the optimal value of the decision variables in an objective function, given certain constraints. In this case, an optimization model is used to maximize profit for the agricultural producer, and the decision variables are the amount of acreage allocated to each level of deficit irrigated crop, which, in turn, determines the amount of water used for crop yields and the amount leased to another entity. For this purpose, an optimization model is preferred to a simulation model, which allows the user to identify the impact of a change in different variables but does not ultimately produce an optimal solution.

It should be noted, however, that optimization models have their own shortcomings when used to calculate the value of the objective function using very specific input data. The results from the model used in this thesis, and likely in all of the following publications, are specific to the data, location, price structures, and growing conditions that were used to create the model. The results from one optimization model typically cannot be extrapolated directly for use in other situations. That being said, since the objective of this thesis is to maximize producer profits, it is still the most appropriate model available.

Two of the better known water optimization models are the Water Optimizer (WO) tool, developed at the University of Nebraska – Lincoln, and the Crop Water Allocator (CWA), created at Kansas State University. The WO tool is a Microsoft Excel spreadsheet that takes user entered inputs such as acreage, soil type and water source and determines the profit-maximizing crop mixture, and necessary water requirements, allowing users to choose from single or multiple year optimizations as well as choosing between one to five fields for the analysis.

Similar to the WO tool, the CWA is a decision tool that allocates water among two to six crops and up to five different land divisions (Klocke et al, 2006). Net profit is calculated for each combination of water, crop choice, and land division and the results are then ranked for the irrigator to evaluate. As with the model used in this paper, both of these models determine the profit-maximizing outcome based on choices made about acreage and crop mix. However, they are specific to growing conditions and irrigation technologies in Kansas and Nebraska and while they do allow for deficit irrigation, and for fallow as a crop option, they do not allow for leasing when calculating the economic return on a farmer's water right. Since this paper is looking specifically at deficit irrigation as a means of conserving water, fallow is not offered as an option when determining maximum profits.

Further examples of studies that utilize optimization models to determine best agricultural management practices include Bryant et al. (1993), who created a model that allocates irrigation water to one of two fields, or neither, making irrigation decisions 15 times per season in order to maximize expected net returns. As with this thesis, the objective is the maximization of expected net returns. The variables include soil water for each field, yield per crop, and quantity of water per irrigation. Again, temporary or permanent fallowing is an available option but leasing is not included as part of the objective function as it is in this thesis.

Bernardo et al. (1987) used a two-stage simulation and mathematical programming model to allocate acreage, water, and other limiting inputs among four different crops to determine maximum returns given four different levels of irrigation. They looked specifically at the effect that changes in the available water supply have on farm income for both center pivot and surface irrigation scenarios.

Mushtaq and Moghaddasi (2011) conducted research on the use of DI on several crops in the Murray Darling Basin of Australia. They too used an optimization model to maximize profit from a combination of crop production and potential water leasing. As with this thesis, part of their focus was on increased interest in improved environmental flows. The authors compared income at both full irrigation and different levels of DI to monitor potentially foregone profits. They found that while results varied between crops, for instance tomatoes and pasture are much more sensitive to water stress than wheat is, valuing the conserved water using local water trading prices can result in increased overall gross margins for the irrigator.

There is much research available that looks at using deficit irrigation during drought years, or in areas with less-defined water laws than Colorado where water supply is uncertain, but there is very little conversation focusing on DI as part of a comprehensive farm management program that includes leasing part of the producer's water right. The aim of this thesis is to contribute to that literature by supplying further results and discussion on maximizing profits through leasing and crop growth.

CHAPTER 4: ANALYTICAL FRAMEWORK

In order to assess the potential profits, it was first necessary to determine the variables needed for calculating farm revenue and costs. The following equations served as a guideline for the fundamental components of the model used in this thesis. The explanation of inputs begins with the basic profit function

(4.1) $$\pi = R - C$$

Where π is profit, *R* is the total revenue function, and *C* is the total cost function. The estimated revenue from irrigation can be represented as a product of the per acre crop yield *Y* and the crop price

(4.2) $$R\ (w_i) = \sum_{i=1}^{n} (p_i * \ Y(w_i) * a_i)$$

Where *p* is the price for crop *i* = 1 to *n*, w_i is the amount of water consumed by crop *i* on a per acre basis, and *a* is the amount of acreage allocated to that crop. In this case, lease payments are also considered when calculating the revenue equation and are shown as follows

(4.3) $$R\ (w_l) = \ \Sigma(r * w_l * \ a_l)$$

Where r is the lease payment received per acre-inch of water and w_l is the amount of water leased per acre. This is assuming that, historically, a certain amount of water is used per acre for full irrigation application, but in this situation some of that water is being leased instead. Combining the two sources of revenue gives

$$(4.4) \qquad R = R(w_i) + R(w_l)$$

The costs of production, *C*, include expenses undertaken during the pre-harvest and harvest stages, including irrigation energy, fertilizer, maintenance, and labor. In order to allow them to vary across the different levels of yields that will result under deficit irrigation, the variable costs, with the exception of fertilizer, are determined on a dollar per bushel or per pound basis. Fertilizer is determined through production functions specific to each crop that take into account yield and crop price. The fixed costs are determined on a per acre basis and are different for each crop. As such the cost equation is as follows

$$(4.5) \qquad C_i = VC_i + FC_i$$

Where *VC* is the variable costs for crop *i,* determined on a per bushel or pound basis, and *FC* is all other costs. This is assuming there are no production costs to the farmer of participating in the leasing agreement.

The farmer's problem in this thesis is a slight twist on the basic producer's problem in which the firm chooses its inputs and outputs based on market prices with the goal of maximizing profits. Rather than choosing an output level based solely on crop yields and prices, the representative producer will choose which crops to allocate land and irrigation water to, as well as the amount of water to lease, if any. In effect, this treats leasing as a separate crop option for the farmer.

The farmer's objective is to maximize profit by allocating water between the two competing uses and, as such, the objective function is equivalent to the profit function given below in Equation 4.6. Combining the two previously described sources of revenue with the cost function, and using *W* as the total amount of water available for all purposes, the profit function can be displayed as

$$(4.6) \qquad \pi\,(W) = (\textstyle\sum_{i=1}^{n}(p_i * \ Y(w_i) * a_i)\,) + \ \Sigma(r * w_l * \ a_l) - (VC_i + \ FC_i)$$

While it is faster and more convenient to use a computerized optimization model to solve the above profit function, it is also illustrative to understand the criteria that the model uses when allocating resources between competing uses. With that in mind, Equation 4.7 shows a slight variation of the profit function above, in that it calculates profit at the farm level rather than on a per acre basis.

$$(4.7) \qquad \pi = \ \Sigma(p_i * \ Y_i) + \ r * \ w_l - c(Y_i, w_l)$$

Where p_i and r are the price of crop i and the leasing payment, respectively. Y_i is the farm level output of crop i and can also be defined as

(4.8) $$Y_i = f(w_i|X)$$

Where w_i is the acre-feet of ET consumed on the farm and X is the set of input values applied to the farm. This is a constrained optimization and, as such, there are constraints on available water and on the minimum amount of water consumed by crops. The constraint on available water is described as

(4.9) $$W - EP \geq w_i + w_l$$

Where W is equal to total available water that can be allocated to either crop growth, w_i, or leasing, w_l, minus the amount of water that comes from effective precipitation. As previously mentioned, the only water that a farmer can conserve and then lease is ET. However, the part of ET that comes from effective precipitation cannot be leased, because that amount will change from year to year and is not known until the end of the growing season.

The second constraint is on the minimum amount of water that is consumptively used by crops. This constraint was included in order to keep the focus on using deficit irrigation and to ensure that a portion of the water right is used for crop growth. The constraint is set just below one acre-foot per acre, the amount needed to grow winter wheat at the lowest level of irrigation, and is described as

(4.10) $$\Sigma w_i \geq minimum\ ET$$

With the profit function and constraints defined, the Lagrangian multiplier method is now used to describe the conditions for solving a constrained maximization problem.

(4.11) $\mathcal{L} = \Sigma(p_i * Y_i) + r * w_l - c(Y_i, w_l) + \lambda(W - EP - w_i - w_l) + \mu(\Sigma w_i - \min ET)$

The added variables λ and μ are the Lagrangian multipliers and are used to describe the relationship between the objective of maximizing profits and the constraints on the amount of water available and the water consumed by crops. Additionally, they are equal to the amount that total profit would change given a one-unit increase in available water, also referred to as the shadow price. The first order conditions for a maximum solution are as follows

(4.12) $\frac{\partial \mathcal{L}}{\partial w_i} = \Sigma p_i * \frac{\partial \mathcal{L}}{\partial Y_i}\frac{\partial Y_i}{\partial w_i} - \frac{\partial c}{\partial Y_i}\frac{\partial Y_i}{\partial w_i} - \lambda + \mu \leq 0$

(4.13) $\frac{\partial \mathcal{L}}{\partial w_l} = r - c'(w_l) - \lambda \leq 0$

(4.14) $\frac{\partial \mathcal{L}}{\partial \lambda} = W - EP - w_i - w_l \geq 0$

(4.15) $\frac{\partial \mathcal{L}}{\partial \mu} = \Sigma w_i - \min ET \geq 0$

Equation 4.12 shows that the value of a one-unit change in the amount of water consumed by crops is equal to the marginal value product (MVP) of growing crop *i,* minus the marginal factor costs (MFC) associated with that crop.

The cost function in Equation 4.13 is considered small enough to be removed from the equation. There are costs associated with leasing water, such as weed removal due to less dense crop cover, but those particular costs are not explored in this thesis. For equation 4.13, the value of increasing leased water by one unit is simply the lease price, *r.* Equations 4.14 and 4.15 describe the constraints that must be met when calculating the maximum.

The first two equations can be set equal to zero, and therefore can be set equal to λ. In theory, this allows the model to determine which of the two competing uses has the highest shadow price. Alternatively, the two equations could be set equal to each other, solved for w_i, which could then be plugged into Equation 4.14 to determine w_l. These would then be the profit-maximizing values of water applied to crop growth and water supplied in the leasing agreement.

The inputs that make up the previous functions, either directly or indirectly, include: crop price data, anticipated lease pricing, precipitation data, costs associated with managing and maintaining a productive farm, crop ET requirements, and production functions for each of the four crops. This data was acquired from numerous sources, as described in the data section of the following chapter.

CHAPTER 5: METHODOLOGY

Study Area and Representative Farm

The South Platte River drains 18,924 square miles of northeastern Colorado, including much of the Front Range corridor and notably the Denver metropolitan area. Nine trans-mountain diversions import over 400,000 acre-feet annually into the South Platte River Basin to supply water to the roughly 3 million people that live there (Jones and Cech, 2009). The river begins in the Rocky Mountains near South Park, Colorado and leaves Colorado for Nebraska at the northeastern corner of the state.

The representative farm used in this thesis is an irrigated farm in Weld County, Colorado, part of the South Platte River Basin. The representative farm is 1000 acres in size with a per acre water right of three acre-feet and the model was run using corn, wheat, sunflowers, and dry beans with the acreage fully planted for each scenario. The acreage was determined using the expertise of Dr. James Pritchett, Associate Professor at Colorado State University, and is consistent with the size of a commercial farming operation that might participate in a DI leasing arrangement. The available water for these scenarios is based on the historic consumptive water use of a farm growing these crops at full irrigation.

Economics of Deficit Irrigation

Crop yield response to consumptive water use is needed, in order to predict yield when using less than the full irrigation amount. Since this response is specific to plant and location, it is necessary to use crop-specific production functions. This thesis uses crop water production functions based on the data from the USDA DI research farm, which is further described in the data section of this chapter. The shape of each production function curve serves as an indication of that crop's response to a limited irrigation schedule.

As previously mentioned, the crop water production curves characterize the relationship between yield and ET, also referred to as the water use efficiency (WUE). From an economic perspective it is helpful to review the profit functions associated with these curves. This thesis uses both WUE, to understand how the relationship between yield and ET affect a crop's suitability to DI, and the crop profit functions, to assess the potential profitability of growing DI crops.

The crop water production functions are combined with fixed and variable costs to produce profit functions. If, when fixed and variable costs are included, the relationship between ET and profit is linear, it indicates that there is little or no change in the marginal value of water to the farmer. If the marginal value of water is constant, then there is no point along the curve where the opportunity cost of irrigation water increases, and where it might be more efficient to lease some of the consumptive use. The optimal amount of crop growth will likely be at full irrigation or not at all. Figure 5.1 gives an example of this relationship, showing the per acre profit function using a crop water production function estimated from all available years of USDA wheat data, with 2011 costs and prices. As explained later in this chapter, the model uses combined crop water production functions for each of the four crops. The results below do not include revenue from leasing.

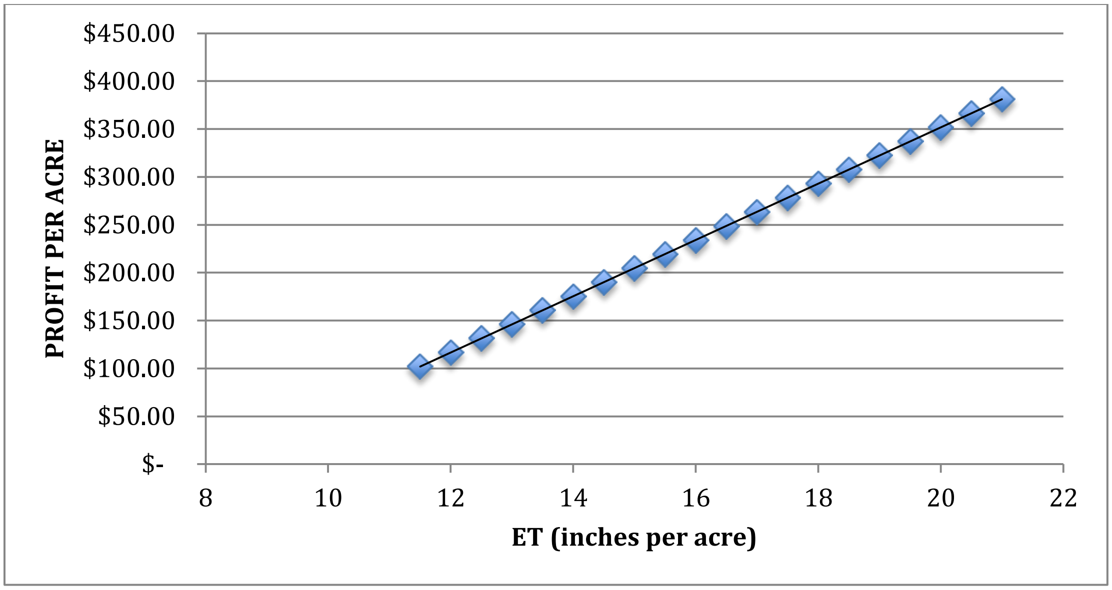

Figure 5.1: Profit function for wheat – combined production function, 2011 prices

However if the variable costs associated with growing the crop are such that the relationship between ET and profit is curvilinear, then there may be a point where it is economically beneficial for the farmer to reduce crop growth and apply that water to its alternative use. As this thesis is specific to Colorado it should be noted that state water law does not permit the expansion of irrigated acreage, which is why leasing is the only example given as an alternative use. Figure 5.2 shows the per acre profit function for wheat grown in 2010 using the production function, costs, and prices specific to that year. It serves as an example of a crop that maximizes profit prior to full irrigation. The maximum profit of $268 per acre is achieved at 18.5 inches per acre, while at the full irrigation level of 19.1 inches per acre, profit is $266 per acre. While the differences in ET and profit are small, it is interesting to note the distinction.

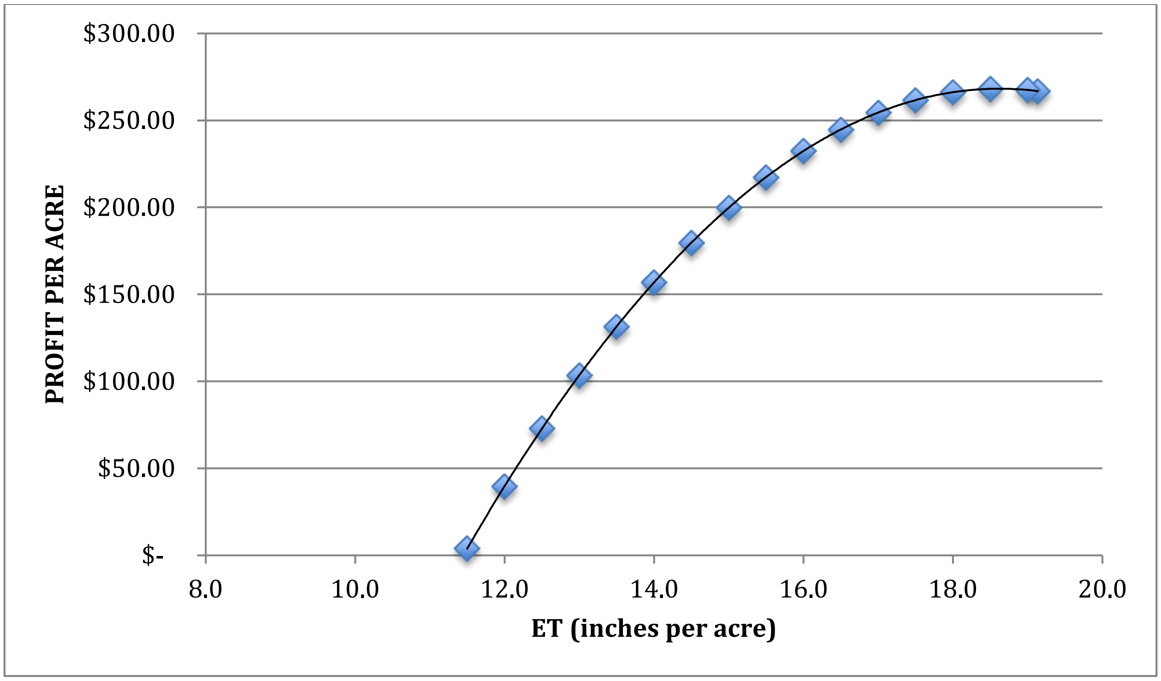

Figure 5.2: Profit function for wheat 2010

The WUE of each of the crops, and the potential implications of those curves, are examined first, followed by a discussion on the profit functions. The remaining figures in this section, along with tables showing the estimated production and profit equations, are located in Appendix A. Figure A.1 shows the crop water production functions for corn, for 2008 – 2011. With the exception of 2010, the curves are relatively linear indicating that corn grown in Northeast Colorado is not a likely candidate for DI. The model will most likely choose to either fully irrigate corn, or not grow corn at all.

The crop water production functions used in this thesis were estimated by combining yield and ET data, across all four years, for each crop. A graph was first created by plotting the data points from each year, and then a best-fit trendline was run through those points to estimate the equation used in the model. Figure A.2 shows the production function that was used for corn. Again, it displays a relatively linear relationship between ET and yield.

If the WUE of a crop is not constant, and instead the curve gets flatter as full irrigation is reached, then there may be a benefit to deficit irrigating that crop. In Figure A.3, the production curves for wheat in 2009, and particularly 2010, are examples of this relationship. There is a point at which crop growth starts to decrease and WUE declines. Based on the studies detailed in the Literature Review of this thesis, crops that maximize WUE prior to full irrigation tend to perform better under limited irrigation than those with linear curves. As further illustration of this, Table 5.1 shows the actual WUE of wheat at each level of irrigation. These numbers are calculated by dividing yield at each level of irrigation by the amount of water consumptively used by the crop, otherwise known as ET. For all years, WUE is maximized below full irrigation, evidence that there could be an economic benefit to deficit irrigating wheat. While maximizing WUE is not the objective of this thesis, it is an indication of the potential success of DI.

Figure A.4 shows the combined production function for wheat. When estimated using all three years, the curvilinear shape of 2009 and 2010 is obscured but the trend line necessarily reflects the range of possible outcomes given different years.

Table 5.1: Water use efficiency of wheat 2009 – 2011

WUE: Yield/ET			
Target %	**2009**	**2010**	**2011**
100	12.7	14.3	11.3
85	12.2	15.5	11.6
70F	15.1	16.2	11.4
70	11.6	15.9	12.5
55	12.2	15.2	11.9
40	6.7	10.9	13.9

The production curves for beans are not as cleanly interpreted as wheat and corn. Figure A.5 reflects the variation that can occur from one season to the next. Beans have a growing season similar to that of sunflowers and corn but are clearly more sensitive to changes in effective precipitation and irrigation. This is consistent with what Webber et al. (2006) found in their study of the common bean. The combined production function for beans is shown in Figure A.6.

Figure A.7 shows the three available years of sunflowers. Sunflowers are fairly consistently linear, with one year of higher precipitation causing a shorter curve. In contrast with beans, the combined production function, given in Figure A.8 for sunflowers, is very similar in shape to the individual years' curves.

To better understand the profits associated with the crops, and to assess how the model is likely to allocate water to a given crop, Figure A.9 shows the profit functions for corn, wheat, and sunflowers using the combined production functions and 2010 prices. The price of dry beans was particularly low in 2010, leading to negative profits at most levels; for this reason it is not included in the graph.

As with the WUE curves, the profit curves are linear, meaning that marginal profit is constant across all levels of crop yield. Typically, the ideal output level matches up with the point on the profit curve where marginal profit decreases to zero and marginal revenues and costs are equal. This point indicates that there is no further opportunity to increase profits. Since marginal profit does not decrease when an additional unit of yield is produced, profit is not maximized until full irrigation. Based on these curves, a deficit-irrigated crop would not be chosen as the profit maximizing choice. If the model chooses a particular crop as the profit maximizing option, then it will be grown at full irrigation.

Optimization Model

In the model used in this thesis, profit is maximized through crop growth and water leasing. Total revenues from crop growth are determined by crop price and yield, which is based on the amount of acreage optimally allocated to each crop. Using the acreage per crop, the model calculates total crop yield at each level of irrigation, crop revenue, total water used for crop growth, amount of water leased, total fixed costs based on acreage, and total variable costs based on crop yield. Fixed and variable costs are equivalent to the most recent cost data, the 2011 Enterprise Budgets. Fixed costs include pre-harvesting costs such as seed, fuel, maintenance, and labor. Variable costs include energy and harvesting costs.

Nitrogen fertilizer costs are determined separately, with production functions specific to each crop. The production function for corn (Shapiro et al, 2008) is based on expected yield and a price adjustment factor that includes the price of corn and nitrogen. This ensures an optimal amount of nitrogen based on expected economic returns. The production function for sunflowers is based on expected yield and the one for wheat is based on a ratio of crop and fertilizer prices. The equation used came from the High Plains Sunflower Production Handbook, a collaborative effort between the USDA Agricultural Research Service and several universities. Beans are nitrogen-fixing and thus do not require additional nitrogen.

The nitrogen application for wheat is the only one that is the same at each level of deficit irrigated crop because it is based only on price and not on expected yield. According to Ferguson (2006), wheat is different from most crops in that higher yields do not require higher nitrogen application rates, which is why expected yield is not factored into the equation. The equation is entered into the model in such a way that the maximum allowable nitrogen application for dryland wheat is 100 pounds per acre and 150 pounds per acre for irrigated wheat (Ferguson, 2006).

Profits from leasing water are based only on the optimal amount of water allocated toward leasing and the current lease price. It is assumed here that there are no costs associated with leasing for the farmer; those costs are borne by the company that initiates the leasing agreement.

Crop price, lease payment, and the amount of available water are entered prior to running the model. Available water is estimated from the consumptive use of fully irrigated crops from the USDA research farm and is held at two acre-feet, which includes six inches of effective precipitation. The amount of precipitation will of course vary across growing seasons but this is considered an average year and is based on expert advice from Dr. James Pritchett. The model uses a per acre water right of three acre-feet for the representative farm, with fifty percent of water lost through conveyance and application inefficiencies. These types of water losses are consistent with surface irrigated crops, in particular with the use of furrow irrigation. The amount available to lease is net of effective precipitation and is set at 18 inches per acre. Any level of deficit irrigated crop that requires 18 or more inches of ET per acre will not have a leasing option included.

A sensitivity analysis was performed in order to assess the robustness of the optimization model. This helps to determine how sensitive the model results are to changes in the variables and whether a small variation in crop price or leasing payment will have a large effect on either profit or the amount of water leased. Changing the lease and crop prices, and observing the results for each combination, also helps to ensure that they are consistent with expectations.

Additionally, the sensitivity report produced by Excel Solver provides sensitivity analysis for the model. When the constraints, such as available water and acreage, are binding, the report lists the shadow price for that constraint. This is equal to the amount that profit would change if that constraint was relaxed and an additional unit was allowed.

Excel Solver is a set of tools used for building and solving optimization problems. In this case, the objective function that Solver is optimizing is total profit. It does this by changing the variable cells, which, in this model, are the cells that determine the amount of acreage allocated to each level of irrigated crop. The model was solved using the linear solving method, allowing for a maximum of 1000 iterations.

The values for crop price and leasing payment are adjusted to determine the effect on total profit. A range of crop prices was created by using the USDA data and futures prices for corn and wheat as the upper and lower bounds and creating equal intervals for a total of six price levels for each crop. Those prices were used to understand the possible changes in crop choice given the relationship between the different prices. The lease price ranges from $192 per acre-foot to $672 per acre-foot. These prices are based on expert advice from Dr. James Pritchett as well as the results from the sensitivity analysis used to determine the lower bound of a farmer's willingness to accept payment for leased water in each of the four years.

Prior to running the model, the data was first used to estimate the representative farmer's foregone profits. Determining the profits achievable using the full water right, and comparing them to the profits achievable when a portion of the water right is no longer available, illustrates the profits that are at risk for a participant in a leasing agreement.

Using the previously described range of crop prices and lease payments, three scenarios were created to examine their effect on total profit. The first two sets of scenarios use the crop water production functions estimated from the combined yield data. In the first set of scenarios, the representative farmer's minimum willingness to accept payment for supplying water is used as the lease price, along with crop price levels specific to each year, to calculate maximum profits available through leasing, the amount of water leased, and the optimal crop mix.

In a second set of scenarios, the same crop water production functions are used but this time with $300, $450, and $600 as the per acre-foot leasing price. The previously mentioned range of crop prices based on USDA prices and futures prices is used in place of the year-year specific data.

The third and final set of scenarios uses the crop water production functions that are specific to the 2010 data, along with costs specific to that year. This year was chosen based on the shape of the production and profit curves and the higher likelihood of the model selecting deficit-irrigated crops as the profit maximizing option. Again, the representative farmer's minimum willingness to accept payment for leasing water is used as the lease price and the same range of crop prices from above are used to determine optimal crop mix, acre-feet of leased water, and maximum profits.

Data

Much of the data used in this thesis came from USDA research and publications. Crop yield data is from an extensive limited irrigation study conducted by the USDA in Greeley, Weld County, Colorado. Between 2008 and 2011, The Agricultural Research Service (ARS) at USDA planted a 50-acre research farm to monitor water use and measure ET rates to study the effects of deficit irrigation. The four crops used were field corn, sunflower (oil), dry beans (pinto), and winter wheat. They irrigated with groundwater, which was applied through drip irrigation tubes.

All crops at the research farm were managed as usual in terms of planting and fertilization, but were irrigated at six levels that ranged from fully irrigated to 40% of full irrigation. Each of the four crops was planted four times with each being treated to six levels of irrigation, for a total of 96 replications. Four of the five deficit-irrigated replications were irrigated at intervals specific to each growth cycle in order to maximize production. To achieve this, water was mainly applied during the reproductive stage of growth. One of the two replications that received 70% of full irrigation was irrigated at a fixed schedule with the fully irrigated crops. This process requires specific knowledge of crop water stress and irrigation timing, a potential barrier to entry for a farmer interested in implementing DI.

The research team measured soil water content within the top six inches of soil and separately between six inches and six feet and used hourly data from a Colorado Agricultural Meteorological (CoAgMet) Network weather station data to calculate the rate of reference ET. In order to accurately measure the total amount of water actually used by the crops, the researchers used the previously mentioned water balance approach that takes into account precipitation, percolation beyond the root zone and depletion of stored soil water by the crops.

Plant measurements were taken periodically, and water stress indicators were monitored, to determine the response of the crops to the irrigation amounts. At the end of each growing season the quality and quantity of seed yield was recorded. The part of the results that this thesis makes use of are the ET totals, yield totals, effective precipitation, and the WUE of each crop, which is the relationship between ET and yield.

The ET and yield totals were used to create production functions for each crop to be entered into the model and the WUE of each crop will be part of the discussion on the economics of deficit irrigation in the following chapter. The effective precipitation data was used to estimate the amount of ET that was rainfall. Data is unavailable for wheat in 2008 and sunflowers in 2009. Table 5.2 below shows data for winter wheat from the 2009 growing season.

Table 5.2: Wheat Data, 2009

Treatment #	Target %	ET *Inches*	Yield *bu/ac*	WUE Yield/ET
1	100	18.5	81	12.7
2	85	17.1	72	12.2
3	70F	17.0	88	15.1
4	70	14.7	55	11.6
5	55	14.1	59	12.2
6	40	11.9	27	6.7

70F = Fixed irrigation schedule at 70% of full irrigation

This thesis uses crop price data for determining the optimal allocation of the farmer's water right and for illustrating potentially profits from leasing. The price per bushel of winter wheat and corn, and the price per pound of dry beans, was acquired from USDA Colorado Department of Agricultural Market News, using historic data specific to Northeast Colorado. The data used for wheat is from the first report date in August of each of the growing years, for corn and dry beans the prices came from the first report in November of each of the growing years. In all cases, a small range of prices was given for Northeastern Colorado; those prices were averaged to get the final price that was used in the model.

The price per pound of sunflowers was acquired from USDA Economic Research Service's Oil Crops Yearbook. The data used came from November of each of the growing years. The months chosen for report dates were based on USDA usual harvesting dates for field crops.

Additionally, the cost data that is incorporated into the optimization model was acquired through Colorado State University's Extension program using Crop Enterprise Budgets specific to Northeast Colorado. Costs were taken from 2011 Budgets, the most recent fully available data. The yield and ET for dryland wheat is based on information provided by Dr. James Pritchett.

The equations used for optimal nitrogen rates for corn and wheat were acquired through University of Nebraska-Lincoln's Extension program (Ferguson, 2006). The equation used for optimal rates for sunflowers came from The High Plains Sunflower Production Handbook produced by Colorado State University and three other universities. The price per pound of nitrogen fertilizer was acquired from the USDA Economic Research Service using 2011 data.

The following chapter, "Results and Analysis", will discuss in detail the outcomes of the model, using the previously described data. Ultimately, one of the objectives of this research is to determine the amount of water that can be conserved in this type of leasing agreement, given all of the variables. Also of interest is the amount that the company initiating the agreement could expect to pay for a given amount of conserved water. As previously mentioned, for the specific example of Coca-Cola, the replenishment goal is 50 million gallons per year, or just over 150 acre-feet of water. This goal will be used as a benchmark in the following section to better understand the suitability of DI to such leasing arrangements.

CHAPTER 6: RESULTS AND ANALYSIS

The objective of this thesis is to describe cropping choices and net profits for a representative farm that may have the opportunity to lease water as part of a replenishment program. The representative farm has the ability to conserve consumptive use water by altering its crop mix or by engaging in deficit irrigation. The previous chapters outlined the analytical framework and the empirical methodology designed to meet the overall objective. This chapter characterizes the results of the empirical procedure and is organized as follows: an estimation of potentially foregone profits, a description of three farm simulation scenarios, and a detailed explanation of the results of those scenarios.

Before describing the results, it is worthwhile to consider the timing perspective that the modeling framework implies. Economic evaluations can take the form of ex ante or ex post analyses. Ex ante studies use models and previous research in an attempt to predict the likely effect of certain choices or events. Ex post studies assess the impact of those decisions or events and can also be used as part of ex ante predictions or to determine their accuracy. This thesis makes use of both in that it is attempting to predict what choices a representative farmer might make, without the benefit of information on future conditions, but it also analyzes research data to explain what best practices would have been, given historical growing conditions. Simply, the results in this chapter are not a prediction of future performance, but rather they highlight important economic considerations for a potential replenishment program.

Because the economic objective is to maximize farmer profits, the model was first used to calculate potentially foregone profits. These are the profits that a farmer risks by participating in the leasing agreement. By calculating the difference between profits earned when crops are fully irrigated and none of the water is leased, and profits earned when the desired lease quantity was provided without payment, these foregone profits can be used as a proxy for the opportunity cost of applying irrigation water to other uses.

As a reminder, the representative farm in this thesis is a 1000-acre irrigated farm located in Weld County, Colorado with a per acre water right of three acre-feet. The goal is to replenish 154 acre-feet of water each year, which is approximately ten percent of the representative farmer's total water right. In order to determine potentially foregone profits, profits were first calculated for each year, 2008 – 2011, with the leasing option excluded. Profits are calculated according to Equation 4.6. The middle term of this equation, $\Sigma(r * w_l * a_l)$, describes revenues from leasing and is equal to zero in this case, for the purpose of determining baseline profits. Profit levels are described in Table 6.1.

(4.6) $$\pi\,(W) = (\textstyle\sum_{i=1}^{n}(p_i * \; Y(w_i) * a_i)\,) + \; \Sigma(r * w_l * \; a_l) - (VC_i + \; FC_i)$$

To illustrate the data and potential profits for each year, Table 6.1 includes crop prices, the crop choice that maximizes profit, and the profit associated with those choices, for the first part of the foregone profit calculation. Depending on the year, all irrigation water is allocated to either fully irrigated wheat or fully irrigated corn. Maximum profits are based on a single model run, using 2011 costs. These are the results that the representative farmer could expect to realize outside of the leasing agreement.

Table 6.1: Crop prices and maximum profits without leasing

YEAR	WHEAT PRICE	CORN PRICE	BEAN PRICE	SUNFLOWER PRICE	CROP CHOICE (# OF ACRES)	MAX PROFIT WITHOUT LEASING
2008	$7.24	$3.74	$0.27	$0.23	FULLY IRRIG. WHEAT (1000)	$434,914.60
2009	$4.72	$3.58	$0.26	$0.14	FULLY IRRIG. WHEAT (1000)	$199,049.12
2010	$5.21	$5.10	$0.17	$0.19	FULLY IRRIG. CORN (1000)	$447,143.39
2011	$6.68	$6.29	$0.39	$0.29	FULLY IRRIG. CORN (1000)	$684,300.47

The minimum willingness to accept of a farmer initially entering into a leasing arrangement is defined in this research as the difference between profits with full irrigation supplies and profits when irrigation supplies are reduced by 154 acre-feet. Irrigation water supply reduction can induce different cropping choices, so the same optimization model is used to simulate these changing production practices and to calculate the resulting profit levels. The difference between the profit with, and in the absence of, the 154 acre-feet, represents the potentially foregone profits of the decision to lease a portion of the water right.

The second part of calculating foregone profits was determining the maximum profits available to the farmer when 154 acre-feet of the water right were no longer available. Table 6.2 shows the maximum profits achievable without the 154 acre-feet, as well as the crop choices that maximize profit, the potentially foregone profits based on the results in Table 6.1, and foregone profits per acre-foot of water. The maximum profits are based on a single model run, using the same crop prices and costs as the first part of the equation. There is a change in the crop mix between Table 6.1 and Table 6.2 in order to free up the 154 acre-feet, however these results do not include any revenue from leasing.

Table 6.2: Potentially foregone profits of participating in a leasing agreement

YEAR	MAXIMUM PROFITS	CROP CHOICE	POTENTIALLY FOREGONE PROFITS	FOREGONE PROFITS PER AF
2008	$379,306.45	FI WHEAT, DRYLAND WHEAT	$55,608.15	$361.09
2009	$170,638.37	FI WHEAT, DRYLAND WHEAT	$28,410.75	$184.49
2010	$375,530.89	FI CORN, DRYLAND WHEAT	$71,612.50	$465.02
2011	$582,154.01	FI CORN, DI SUNFLOWERS	$102,146.46	$663.29

Scenarios

Table 6.3: Description of model scenarios

SCENARIO	PRODUCTION FUNCTIONS	CROP PRICES	LEASE PAYMENT
1	Combined	Historical price data (2008 - 2011)	Minimum WTA
2	Combined	Custom price range	$300, $450, & $600/AF
3	2010 yield data	Custom price range	Minimum WTA

As shown in Table 6.3, three different scenarios are examined in this chapter. The first two scenarios calculate farm level profits with standard technologies but use crop water production functions that were estimated by combining research plot-level yield data for the years 2008 – 2011. Figures A.2, A.4, A.6, and A.8 depict these functions, and are located in Appendix A.

In the first scenario, the representative farmer's minimum willingness to accept payment for supplying water is used as the lease price, along with crop price levels specific to each year, to calculate maximum profits available through leasing, the amount of water leased, and the optimal crop mix.

In the second scenario, the same crop water production functions are used but this time with $300, $450, and $600 as the per acre-foot leasing price rather than a calculated minimum willingness to accept value. These lease payments are consistent with ongoing lease arrangements for water in the Arkansas River and South Platte Basin. In order to examine how the results change given different ratios between crop prices, a different set of prices is used in this scenario. The upper and lower bounds on the range of prices are based on USDA price data and futures prices. That range was then broken into six equal increments for each crop.

The third and final scenario uses the same crop price range as the previous one, but with crop water production functions that are specific to the 2010 data. Rainfall in April, May, June, and August of that year was all above average, leading to production and profit functions that are more curvilinear than those used in the previous scenarios. This increases the chance that profit will be maximized prior to full irrigation, potentially leading to deficit-irrigated crops being a profit-maximizing choice. As with scenario one, the representative farmer's minimum willingness to accept payment for supplying water is used as the lease price, which was estimated by using crop prices specific to 2010.

Leasing Scenario One

For scenario one, the model was first used to estimate the representative farmer's willingness to accept payment for leasing a portion of their water right. This was determined separately for each year and is the lowest price at which the farmer is willing to supply water. Due to changes in crop prices, the lease payment varies considerably between years. Figure 6.1 displays those amounts. The prices for 2010 and 2011 are on the high end compared to typical lease payments in Northern Colorado.

It should be noted that these amounts were estimated using ex post knowledge about crop yields, prices, and growing conditions. That is, under the assumption that the farmer knows with certainty at planting and lease signing what prices and yields will be at harvest. In reality, farmers have price and yield expectations, which may be different than what is realized.

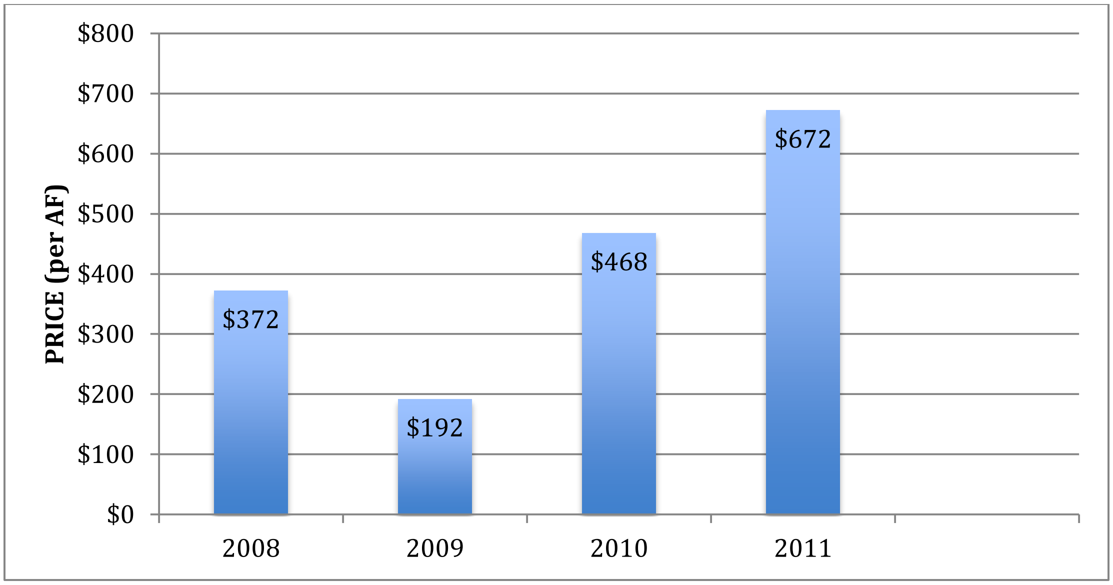

Figure 6.1: Lower bound willingness to accept payment, 2008 – 2011

Using the crop and lease prices specific to each year, the model was then used to determine the optimal amount of water that would be leased, the amount that would be used for crops, and the crop mixture that would maximize profits. In order to allow the model to choose the optimal amount of leased water, that total is no longer constrained at 154 acre-feet. Table 6.4 shows the results of each of those iterations, separated by year.

Table 6.4: Leasing results at the minimum willingness to accept lease payment

	ACREAGE PER CROP CHOICE (PERCENT OF FULL IRRIGATION)					**WATER LEASED (AF)**	**CROP WATER (AF)**
	WHEAT	**DRYLAND WHEAT**	**CORN**	**BEANS**	**SUNFLOWERS**		
2008	231 (100%)	769	0	0	0	641	917
2009	231 (100%)	769	0	0	0	641	917
2010	0	800	200 (100%)	0	0	667	917
2011	0	0	143 (100%)	0	857 (47%)	643	917

The results for 2008 – 2011 vary mainly in the choice between fully irrigated wheat and fully irrigated (FI) corn. In 2011, water is allocated to sunflowers grown at 47% of full irrigation, but while they are treated as an irrigated crop on the USDA research farm, more often they are treated as a dryland crop, like dryland wheat, and are given only supplemental irrigation.

Combining the production functions across the four years resulted in more linear curves, particularly for wheat. As described in the previous chapter, this reduces the likelihood of the model choosing one of the deficit-irrigated crops in the solution, because marginal profit is constant across all levels of production. There is no point where marginal profit decreases until it reaches zero, which would indicate that profit was maximized prior to full irrigation.

Figure 6.2 is a graph of the same profit curves discussed in the Methodology section, this time including a profit curve for leasing. The graph is used as an explanation of why the above results are almost entirely fully irrigated crops. This graph shows that marginal profit is constant and profit is maximized at full irrigation. If a crop is a profit maximizing choice, then water will be allocated to the fully irrigated option. The profit curve for leasing is based on the payment used in the 2010 example above. Depending on the lease payment, the curve will shift up and down relative to the profits earned from crops. The actual profit equations for the crops are shown in Table 6.5, where *w* is equal to inches of consumptive crop water. The R^2 *Values* are included as an indication of how well the trendline fits the data, with *1* being the best fit.

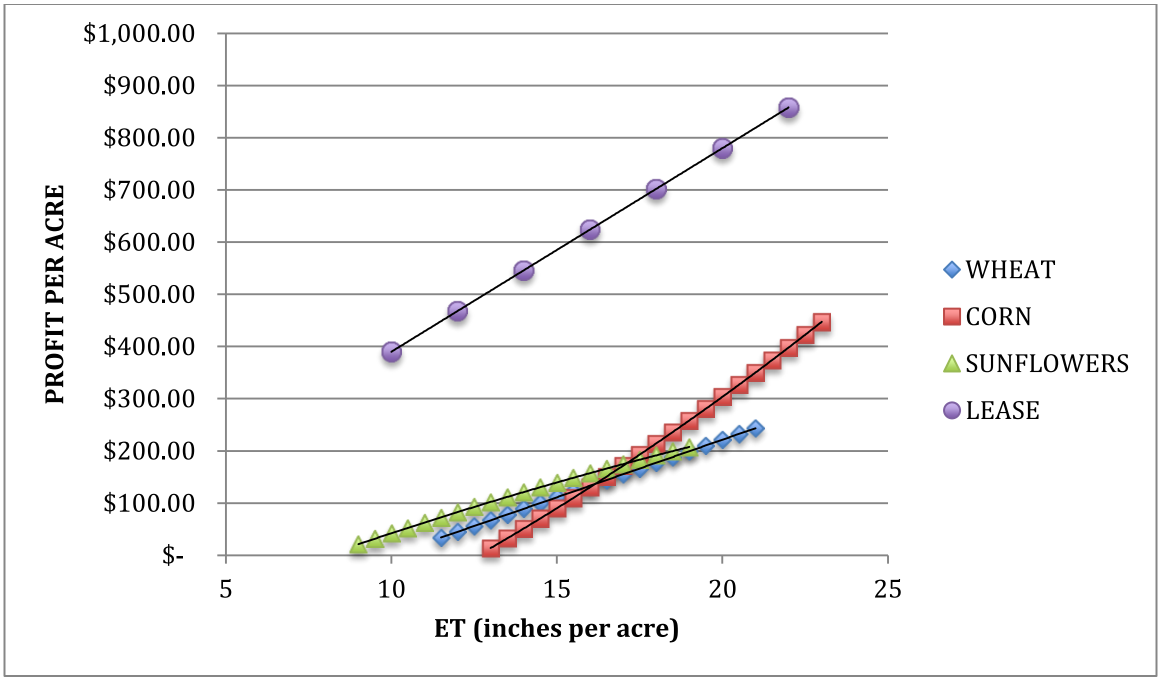

Figure 6.2: Profit functions using combined production functions

Table 6.5: Profit equations using combined production functions

CROP	PROFIT EQUATIONS	R^2 VALUE
WHEAT	$\pi = 0.0049w^2 + 21.899w - 218.53$	1
CORN	$\pi = 0.6487w^2 + 19.984w - 355.64$	1
SUNFLOWERS	$\pi = -0.2725w^2 + 26.281w - 193.41$	1

The optimal results for 2008 and 2009 both allocate all water to fully irrigated (FI) wheat up until the minimum willingness to accept payment is reached. After that point, in both years a total of 641 acre-feet were freed up for leasing by shifting 769 acres from FI wheat to dryland wheat.

In 2010 and 2011, corn price increased relative to wheat price so that the value per acre for corn was higher than the value per acre for wheat. Below the minimum lease payment, all water would optimally be allocated to FI corn. In 2010, when the minimum lease payment is reached, water is allocated to 800 acres of dryland wheat and 200 acres of FI corn, freeing up 667 acre-feet of water for leasing.

The willingness to accept payment for leasing water is highest in 2011, at $672 per acre-foot. At that point, irrigation water is allocated between FI corn and the lowest level of irrigated sunflowers. The price of sunflowers was the highest in 2011, and the nitrogen costs are based on yield, leading to higher profits at lower yield levels. Under this scenario, 643 acre-feet were available for leasing.

In all four years, the amount of water allocated to crops is the same, 917 acre-feet. This is due to the previously mentioned constraint that requires a minimum amount of water to be allocated to crops. In the first three years, if that constraint is removed, all acreage is allocated to dryland wheat and the maximum amount of water is leased. In 2011 the price of sunflowers was particularly high and all acreage would be allocated to the lowest irrigation level of sunflowers, again freeing up the maximum amount of water to be leased. Table 6.6 below displays the profit information for the previously described iterations. The conclusions based on these results are discussed, following the next scenario.

Table 6.6: Leasing profits for 2008 – 2011

YEAR	LEASE PAYMENT	QTY LEASED (AF)	MAX PROFIT WITH LEASING	LEASING - PROFIT PER ACRE	LEASING - PERCENT OF PROFIT
2008	$372	641	$442,155	$442	53.9%
2009	$192	641	$203,992	$204	60.3%
2010	$468	667	$449,467	$449	69.4%
2011	$672	643	$690,149	$690	62.6%

Leasing Scenario Two

In order to better understand the relationship between the different crop prices, and capture the change in leased water, particularly in regard to the ratio between corn and wheat price, the model was next run using a range of prices for each crop. This is a further example of an ex post analysis; farmers are price-takers and do not have the option of determining optimal crop choice and price combinations prior to planting.

As previously mentioned, the range of crop prices uses the USDA price data and futures prices for the upper and lower bounds, with equal intervals set for a total of six price levels for each crop. Three levels of leasing payment were used, $300, $450, and $600 per acre-foot. Those prices were established both from model results and expert advice from Dr. James Pritchett, based on responses to an agricultural survey conducted in Northern Colorado.

Because the sensitivity analysis revealed a pattern of choosing either corn or wheat, or a combination thereof, particular focus was paid to those two crops. Multiple iterations were run and results were recorded for each combination of wheat and corn price at each lease payment. The price for dry beans and sunflowers was held constant. Tables 6.7, 6.9 and 6.10 show the results of those iterations for a lease payment of $300, $450, and $600 per acre-foot, respectively. In order to better understand where leasing takes place, Table 6.8 includes ten-cent increments between prices to offer more detail at the margin between leasing and not leasing water.

Table 6.7: Quantity of water leased at $300 per acre-foot lease price

ACRE-FEET LEASED - $300 LEASE PAYMENT						
Wheat ($/bu)	*Corn ($/bu)*					
	$3.74	**$4.24**	**$4.74**	**$5.24**	**$5.74**	**$6.29**
$4.72	646	667	0	0	0	0
$5.22	641	667	0	0	0	0
$5.72	641	641	0	0	0	0
$6.22	641	641	0	0	0	0
$6.72	0	0	0	0	0	0
$7.24	0	0	0	0	0	0

Different ratios between the corn and wheat price cause water to be allocated in different ways. For instance, an increase in the price of corn causes more water to be leased, while an increase in the price of wheat causes less water to be leased. This is due to the constraint placed on the minimum amount of water consumptively used by crops. When the lease price is high enough relative to crop prices, the model allocates as much water as possible to dryland wheat because that frees up the most water for leasing. In order to meet the constraint on crop consumptive use, in most cases the rest of the water is allocated to fully irrigated wheat or corn. As an example, an increase in the price of corn causes more water to be allocated to fully irrigated corn, but corn uses more water at full irrigation than wheat does so less acreage is required to meet the minimum ET requirement and more water is available to lease. The opposite is true for the wheat example.

The iterations that resulted in 641 acre-feet being the optimal amount leased were based on 231 of the 1000 acres being allocated to FI wheat and 769 acres to dryland wheat. 646 acre-feet were leased when 225 acres were allocated to FI wheat and the rest went to dryland wheat. 667 acre-feet were leased when 200 acres were used for FI corn and 800 acres went to dryland wheat. When all water was allocated to either FI wheat or FI corn the resulting lease total was zero.

Table 6.8: Quantity leased at $300 per acre-foot lease price: ten-cent increments

ACRE-FEET LEASED - $300 LEASE PAYMENT						
Wheat ($/bu)	*Corn ($/bu)*					
	$3.74	**$4.24**	**$4.74**	**$5.24**	**$5.74**	**$6.29**
$4.72	642	667	0	0	0	0
$5.22	641	667	667	0	0	0
$5.72	641	641	667	667	0	0
$6.22	641	641	641	641	667	0
$6.32	641	641	641	641	641	0
$6.42	0	0	0	0	0	0
$6.52	0	0	0	0	0	0
$6.62	0	0	0	0	0	0

Because of the linear profit functions, there are only a couple of crop combinations that maximize profits, and involve leasing, and none of them include deficit-irrigated crops. Again, this is due to constant marginal profits leading to profit being maximized at full irrigation. This means that the model chooses one of two extremes: either no water is leased or else more than 600 acre-feet are leased. In order to allow leasing, the model chooses combinations of either fully irrigated wheat and dryland wheat, or fully irrigated corn and dryland wheat.

Similar results are shown for the other lease prices in Tables 6.9 and 6.10. The combinations of crops are the same but with more water being leased at higher crop prices given the increase in the lease payment.

Table 6.9: Quantity of water leased at $450 per acre-foot lease price

ACRE-FEET LEASED - $450 LEASE PAYMENT						
Wheat ($/bu)	*Corn ($/bu)*					
	$3.74	**$4.24**	**$4.74**	**$5.24**	**$5.74**	**$6.29**
$4.72	667	667	667	0	0	0
$5.22	641	667	667	0	0	0
$5.72	641	667	667	0	0	0
$6.22	641	641	667	0	0	0
$6.72	641	641	667	667	0	0
$7.24	641	641	641	667	0	0

Table 6.10: Quantity of water leased at $600 per acre-foot lease price

ACRE-FEET LEASED - $600 LEASE PAYMENT						
Wheat ($/bu)	*Corn ($/bu)*					
	$3.74	**$4.24**	**$4.74**	**$5.24**	**$5.74**	**$6.29**
$4.72	667	667	667	667	0	0
$5.22	646	667	667	667	0	0
$5.72	641	667	667	667	667	0
$6.22	641	641	667	667	667	0
$6.72	641	641	667	667	667	0
$7.24	641	641	641	667	667	0

Table 6.11 displays the maximum profits available for each of the six price levels used above, at each lease payment, based on the allocation of water shown in the previous tables.

Price level is used in place of the individual crop prices in order to include dry beans and sunflowers in the calculations. Individual crop prices for each level are shown in Table 6.12.

Table 6.11: Maximum profits per price level and lease price

	Price Level					
Lease Price	**1**	**2**	**3**	**4**	**5**	**6**
$300.00	$273,220	$304,161	$376,548	$474,741	$573,965	$684,300
$450.00	$373,032	$404,161	$436,213	$474,741	$573,965	$684,300
$600.00	$473,032	$504,161	$536,213	$569,772	$605,617	$684,300

Table 6.12: Crop prices at each price level

PRICE LEVEL	**CROP**			
	WHEAT	**CORN**	**BEANS**	**SUNFLOWERS**
1	$4.72	$3.74	$0.17	$0.14
2	$5.22	$4.24	$0.22	$0.17
3	$5.72	$4.74	$0.27	$0.20
4	$6.22	$5.24	$0.32	$0.23
5	$6.72	$5.74	$0.37	$0.26
6	$7.24	$6.29	$0.39	$0.29

In the previous tables, water is conserved for leasing by integrating a dryland wheat crop into a fully irrigated rotation. Deficit irrigated crops do not appear in the optimal solutions for the model. The reasoning is intuitive; the greatest value for a unit of water is in leasing to the company, followed by the production of either fully irrigated corn or fully irrigated wheat. The inclusion of dryland wheat, which does not use deficit irrigation, is the only reason that water is available for leasing in the previous tables. Based on historical crop prices, the combined crop water production functions used in this thesis, and the resulting profit functions, DI is not a likely option for conserving agricultural water for the purpose of leasing.

As shown in Table 6.11, profits do not change at the highest price level because no leasing takes place. For price levels 4 and 5, leasing only takes place at the highest lease payment. Given these results, combined with the model consistently allocating water to fully irrigated crops, it is more likely that a farmer interested in leasing water would plant a portion of their acreage and fully irrigate, rather than use deficit irrigation.

As previously mentioned, linear profit functions indicate a constant marginal profit, reducing the likelihood that water will be allocated to any of the deficit-irrigated crops. While this method of using combined production functions does obscure the curvilinear shape of the curves from certain years, it also necessarily reflects the implications of possible yield outcomes and thus, profits. If a crop cannot consistently produce expected yield levels under DI then it is not likely to be used as a conservation method under a leasing agreement where leased amounts are an ex ante decision.

Leasing Scenario Three

However, in order to illustrate the conditions necessary for the successful use of deficit irrigation for water conservation, the following section of this chapter uses the production functions from 2010 in place of the combined ones. The production and profit functions estimated from the 2010 data have a more curvilinear shape, making it more likely that a deficit irrigated crop will be a profit maximizing option for the representative farmer. While the combined production functions are a more realistic tool for anticipating yields and profit, it is also illustrative to review an example of what could result under more idealistic conditions. To that end, the model was adjusted to include the production functions from 2010 for each of the four crops as well as cost data from that year. In order to maintain the focus of using deficit irrigation, dryland wheat was removed as an option.

Using those parameters, the lower bound on the willingness to accept payment for leasing water is $468 per acre-foot. This is the same as the willingness to accept in 2010 using the combined production functions but the allocation of water is different. Instead of the water being allocated to FI corn and dryland wheat, 630 acre-feet are allocated to 840 acres of sunflowers irrigated at 47% of full irrigation and 287 acre-feet are used on 160 acres of corn irrigated at 91% of full irrigation. This allocation frees up 630 acre-feet for leasing.

Using that same lease payment of $468 per acre-foot, multiple iterations were run using the 2010 data and the six price levels previously mentioned. Table 6.13 shows the details of those results and how the water was allocated at each price level. The price levels are the same ones described in Table 6.12.

Table 6.13: Results from 2010 crop water production functions

Price Level	***Crops (% of Full Irrigation)***	***ET (acre-feet)***	***Acres***	***Leased (Acre-feet)***	***Maximum Profit***
1	Wheat (71%) Sunflower (47%)	416 500	333 667	83 500	$304,993.80
2	Wheat (74%) Sunflower (47%)	398 519	308 692	64 519	$348,813.03
3	Dry Beans (97%)	1250	1000	250	$425,930.13
4	Dry Beans (100%)	1292	1000	208	$569,849.20
5	Dry Beans (100%)	1292	1000	208	$714,587.81
6	Dry Beans (100%)	1292	1000	208	$772,483.26

Also of interest is the difference in the profit functions between the combined production functions in Figure 6.2 shown earlier, and the ones specific to 2010. In contrast to the linear curves from the combined production functions, the profit curves using the production functions from 2010, shown in Figure 6.3, are curvilinear. This means that profit is maximized prior to full irrigation leading to a deficit-irrigated crop being a profit maximizing choice. Wheat and corn in particular provide an example of profit maximization prior to full irrigation. Profit per acre for wheat is maximized at 88% of full irrigation at $268 per acre.

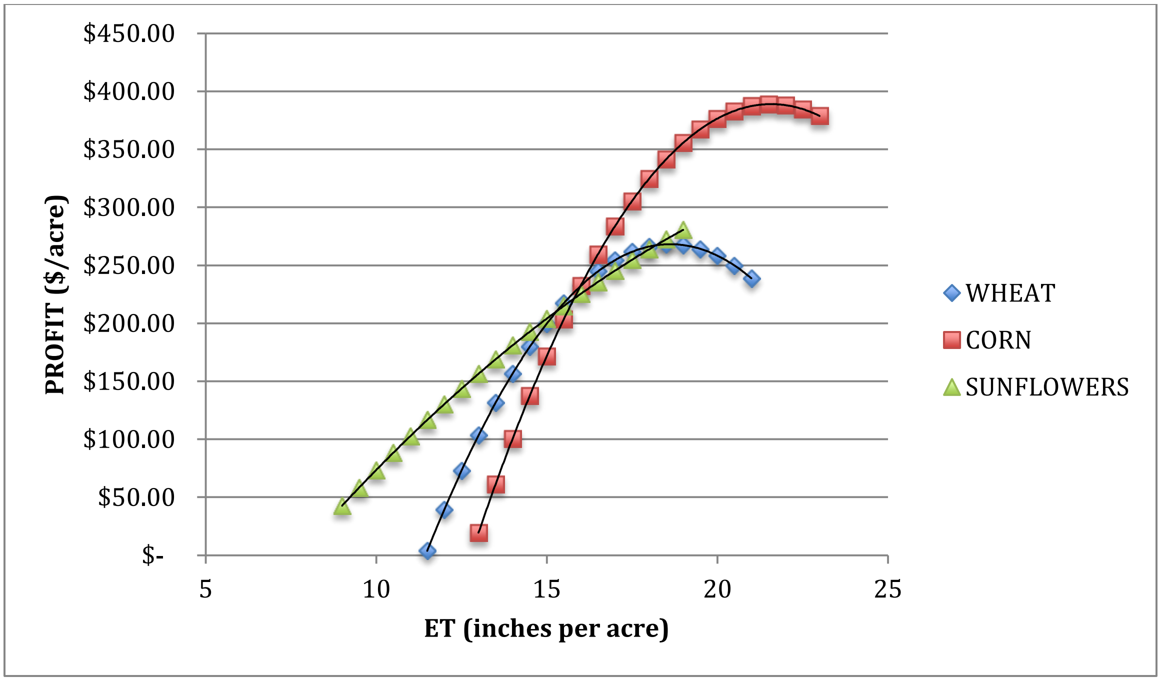

Figure 6.3: Profit functions using 2010 production functions

The curvilinear production and profit functions from 2010 suggest that DI could be an option for the conservation of irrigation water. However, this would only be the case under very specific price and growing conditions. These results are based on the benefit of ex post analysis, so while they are instructive in making ex ante decisions, there is no guarantee of these results. In Table 6.12, four of the six price scenarios show all acreage allocated to beans grown at, or near, full irrigation. While the previous results are interesting and indicate the potential of water conservation while using deficit irrigation, they also illustrate the unpredictability of farm profits and reinforce the conclusion from the first set of results; it is unlikely that a farmer would choose deficit irrigation as a method of participating in a leasing agreement.

CHAPTER 7: CONCLUSIONS, LIMITATIONS, AND FUTURE RESEARCH

The objective of this thesis was to describe some of the conditions under which agricultural water conservation may be used to offset a business's residual water use and to assess whether DI is a practical option for that conservation. To that end, an optimization model was created to determine how water would optimally be allocated between crop growth and leasing, with the objective of maximizing producer profits.

Results were first calculated based on crop water production functions that were estimated using plot level yield data collected from 2008 – 2011. Crop price levels specific to each year were then used to determine the representative farmer's minimum willingness to accept payment for supplying water. These numbers were used as the lease price to calculate maximum profits available through leasing, the amount of water leased, and the optimal crop mix. With the exception of 2011, when the sunflower price was particularly high, all water was allocated to a combination of dryland wheat and either fully irrigated corn or fully irrigated wheat. Sunflowers grown at 47% of full irrigation were the only deficit irrigated crop chosen in all four years.

In a second set of iterations, the same crop water production functions were used but this time with $300, $450, and $600 as the per acre-foot leasing price. A more varied set of crop prices was used in order to understand the possible changes in results given a change in the ratio of those prices. The results were similar to the first set in that all water was allocated to a combination of dryland wheat and either fully irrigated corn or fully irrigated wheat. Because the crop prices increased simultaneously there was no point where sunflower price was high relative to other crop prices and no deficit-irrigated crops were chosen in these iterations.

Under the assumptions used in this model, deficit irrigation is not an option for creating reliable water conservation that can be leased to a third party. In order to determine if a more ideal scenario could produce different results, the model was next used to calculate maximum profits using the crop water production functions from the 2010 data.

Using 2010 crop prices and costs, the representative farmer's minimum willingness to accept payment for leasing water was determined. That result was used as the lease price and the same range of crop prices from above were used to determine optimal crop mix, acre-feet of leased water, and maximum profits. In the two lower price levels, the crop mix was a combination of deficit irrigated wheat and sunflowers, and almost 600 acre-feet were freed up for leasing. With the four higher price levels, all of the water went to beans at or near full irrigation. Beans use less water than the other crops at full irrigation so just over 200 acre-feet were available for leasing but no DI crop was chosen in the crop mix. As with the first two sets of calculations, the results from these iterations indicate that deficit irrigation of the crops presented in this thesis is not a profit-maximizing approach for the representative farmer seeking to lease water to a third party. Instead, using a combination of a fully irrigated crop and a dryland crop is a more profitable opportunity.

As mentioned in the Literature Review chapter, there are certain limitations to using an optimization model. Specific to this model, those limitations include: the estimation of production functions using only four years of field data, the use of very specific growth conditions and tillage practices, and the lack of experimentation with cost data to determine the effect on the shapes of the profit and production functions.

A potential extension of this research would be to include additional crops, specifically alfalfa, as it is a water intensive crop, and is grown in Northern Colorado. Also, including uncertain water availability, as opposed to a guaranteed water right, would improve the applicability of the model and results.

Additionally, there are potential consequences, both from deficit irrigating and leasing part of a water right, that are not explored in this research. The technique of deficit irrigation is recent enough that the infrastructure of farming is still catching up. For instance, the Federal Crop Insurance Program has not yet established expected yield totals for DI crops and instead insures those crops at the same rates as lower producing dryland crops (Trout, 2012). The effects of this, and other issues that may arise from using deficit irrigation, should be fully explored.

Further research is also needed on the long-term effects of leasing a portion of one's water right. Colorado water law bases a water right on historical consumption, and water rights can be lost if not put to a beneficial use (Water Information Program). This could put producers at risk of reducing their water right and at the very least needs to be understood by businesses attempting to develop guidelines for leasing that water.

This thesis would also benefit from the inclusion of two components that are critical to any farmer considering the use of DI as a technique for water conservation. First, the model used in this research is a single-season model that cannot take into account the benefits of crop rotation, seasonal variability in precipitation, or the potential of following one crop with another. To be truly beneficial, there needs to be the added option of customizing the model to include multiple seasons and additional crops.

Lastly, the potential for drought years, hailstorms, and other unplanned disasters is not included in this thesis. Foremost in a farmer's mind when making ex ante decisions such as crop choice, and in this case, leasing quantities, is the risk involved in those selections. Combining the optimization model used in this research with a simulation model for quantifying risk would greatly improve the robustness of the model results.

REFERENCES

Barchart.com Inc. "Futures Market Overview." Accessed May 2013. http://www.barchart.com/futures/marketoverview

Bernardo, Daniel J., Norman K. Whittlesey, Keith E. Saxton, and Day L. Bassett "An Irrigation Model for Management of Limited Water Supplies." *Western Journal of Agricultural Economics* 12, no 2(1987): 164-173.

Bryant, Kelly J., James W. Mjelde, and Ronald D. Lacewell "An Intraseasonal Dynamic Optimization Model to Allocate Irrigation Water Between Crops." *Amer. J. Agr. Econ.* 75(1993): 1021-1029.

Colby, B.G. "Enhancing Instream Flow Benefits in an Era of Water Marketing." *Water Resources Research* 26, no 6(1990): 1113-1120.

Colorado Agricultural Water Alliance. "Can Agricultural Water Conservation and Efficiency Provide the Water Needed for Colorado's Future?" Accessed May 2013. <http://coagwater.colostate.edu/docs/brochure.pdf>

Colorado State University Extension. "Crop Enterprise Budgets." Accessed March 2013. <http://www.coopext.colostate.edu/ABM/cropbudgets.htm>

Colorado State University, Kansas State University, University of Nebraska, University of Wyoming, and USDA-ARS. "High Plains Sunflower Production Handbook." (2009).

Colorado Water Conservation Board. "Instream Flow Program." Accessed May 2013. <http://cwcb.state.co.us/environment/instream-flow-program/Pages/main.aspx>

Fereres, E., and M.A. Soriano. "Deficit Irrigation for Reducing Agricultural Water Use." *Journal of Experimental Botany* 58, no. 2(2007): 147-159.

Ferguson, Richard B. "EC06-155 Nutrient Management for Agronomic Crops in Nebraska" (2006). *Historical Materials from University of Nebraska-Lincoln Extension.* Paper 1711.

Geerts, S., and D. Raes. "Deficit Irrigation as an On-Farm Strategy to Maximize Crop Water Productivity In Dry Areas." *Agricultural Water Management* 96, no. 9(2009): 1275-1284.

Hoekstra, A.Y. "Water Neutral: Reducing and Offsetting the Impacts of Water Footprints." *Value of Water Research Report Series* no. 28(2008).

Jones, P. Andrew, and Tom Cech. *Colorado Water Law.* Colorado: University Press, 2009.

Kansas State University. "Mobile Irrigation Lab Kit and Resources." Accessed February 2013. <http://www.ksre.ksu.edu/mil/ToolKit.htm>

Karam, Fadi, Rafic Lahoud, Randa Masaad, Rabih Kabalan, Joelle Breidi, Claude Chalita, and Youssef Rouphael "Evapotranspiration, Seed Yield, and Water Use Efficiency of Drip Irrigation Conditions." *Agricultural Water Management* 90 (2007): 213-223.

Klocke, N.L., L.R. Stone, G.A. Clark, T.J. Dumler, and S. Briggeman. "Water Allocation Model for Limited Irrigation." *Applied Engineering in Agriculture* 22, no. 3 (2006): 381-389.

Loomis, John B. "Comparing Households' Total Economic Values and Recreation Value of Instream Flow in an Urban River." *Journal of Environmental Economics and Policy* 1, no. 1(2012): 5-17.

Mushtaq Shahbaz and Mahnoosh Moghaddasi. "Evaluating the Potentials of Deficit Irrigation as an Adaptive Response to Climate Change and Environmental Demand." *Environmental Science and Policy* 14(2011): 1139-1150.

Nel, D.C., C. Marais, and J.N. Blignaut. "Water Neutrality: A First Quantitative Framework for Investing in Water in South Africa." *Conservation Letters* 2(2009): 11-18.

Nikouei, Alireza, Mansour Zibaei, and Frank A. Ward "Incentives to Adopt Irrigation Water Saving Measures for Wetlands Preservation: An Integrated Basin Scale Analysis." *Journal of Hydrology* 464-465(2012): 216-232.

Shafroth, Patrick B., Andrew C. Wilcox, David A. Lytle, John T. Hickey, Douglas C. Andersen, Vanessa B. Beauchamp, Andrew Hautzinger, Laura E. McMullen, and Andrew Warner. "Ecosystem Effects of Environmental Flows: Modeling and Experimental Floods in a Dryland River." *Freshwater Biology* 55(2010): 68-85.

Shapiro, Charles A., Richard B. Ferguson, Gary W. Hergert, and Charles S. Wortmann. "Fertilizer Suggestions for Corn, EC117" (2008). *University of Nebraska-Lincoln Extension.*

The Coca-Cola Company. "Collaborating to Replenish the Water We Use." Accessed May 2013. <http://www.coca-colacompany.com/collaborating-to-replenish-the-water-we-use>

Trout, Tom, Walter Bausch, and Gerald Buchleiter. "Does Deficit Irrigation Give More Crop Per Drop?" *Proceedings of the 22nd Annual Central Plains Irrigation Conference, Kearney,NE.,* February 24-25, 2010.

Trout, Tom and Walter Bausch. "Water Production Functions for Central Plains Crops" *Proceedings of the 24th Annual Central Plains Irrigation Conference, Colby, KS.,*February 21-22, 2012.

Turner, Brenda and Gregory M. Perry "Agriculture to Instream Water Transfers Under Uncertain Water Availability: A Case Study of the Deschutes River, Oregon." *Journal of Agricultural and Resource Economics* 22 no. 2(1997): 208-221.

University of Nebraska-Lincoln. “Decision Making at Work for Nebraska.” Accessed February 2013. <http://agecon.unl.edu/wateroptimizer/download.html>

USDA-Agricultural Marketing Service. “Market News.” Accessed February 2013. <http://www.ams.usda.gov/AMSv1.0/marketnews>

USDA-Economic Research Service. “Oil Crops Yearbook.” Accessed February 2013. <http://www.ers.usda.gov/data-products/oil-crops-yearbook.aspx#.UdR4kD5oSPc>

Ward, Frank A., and Manuel Pulido-Velazquez. “Water Conservation in Irrigation Can Increase Water Use.” *Proceedings of the National Academy of Sciences* no. 47(2008): 18215-18220.

The Water Information Program. “Colorado Water Rights.” Accessed May 2013. <http://waterinfo.org/rights.html>

Webber, H.A., C.A. Madramootoo, M. Bourgault, M.G. Horst, G. Stulina, and D.L. Smith “Water Use Efficiency of Common Bean and Green Gram Grown Using Alternate Furrow and Deficit Irrigation.” *Agricultural Water Management* 86(2006): 259-268.

APPENDIX A

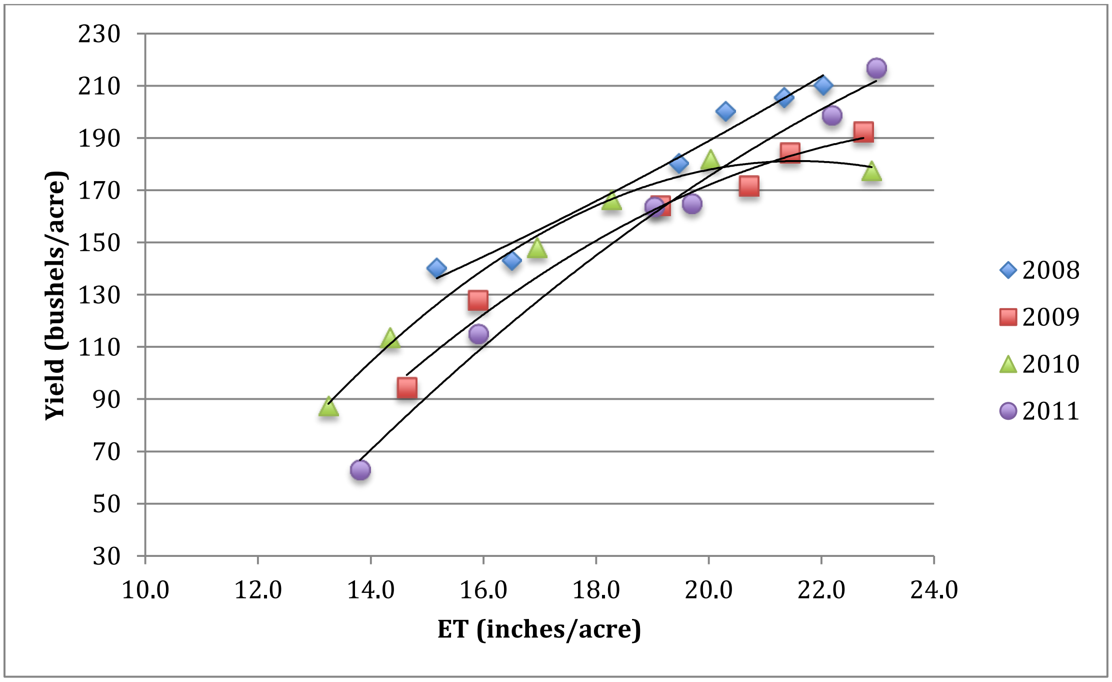

Figure A.1: Water production functions for corn, 2008 – 2011

Table A.1: Production equations for corn, 2008 – 2011

CORN	PROFIT EQUATIONS	R^2 VALUE
2008	$\pi = 0.2183w^2 + 3.2132w + 37.277$	0.97
2009	$\pi = -0.8658w^2 + 43.566w - 353.03$	0.98
2010	$\pi = -1.339w^2 + 57.785w - 442.26$	0.99
2011	$\pi = -0.5761w^2 + 37.038w - 335.04$	0.99

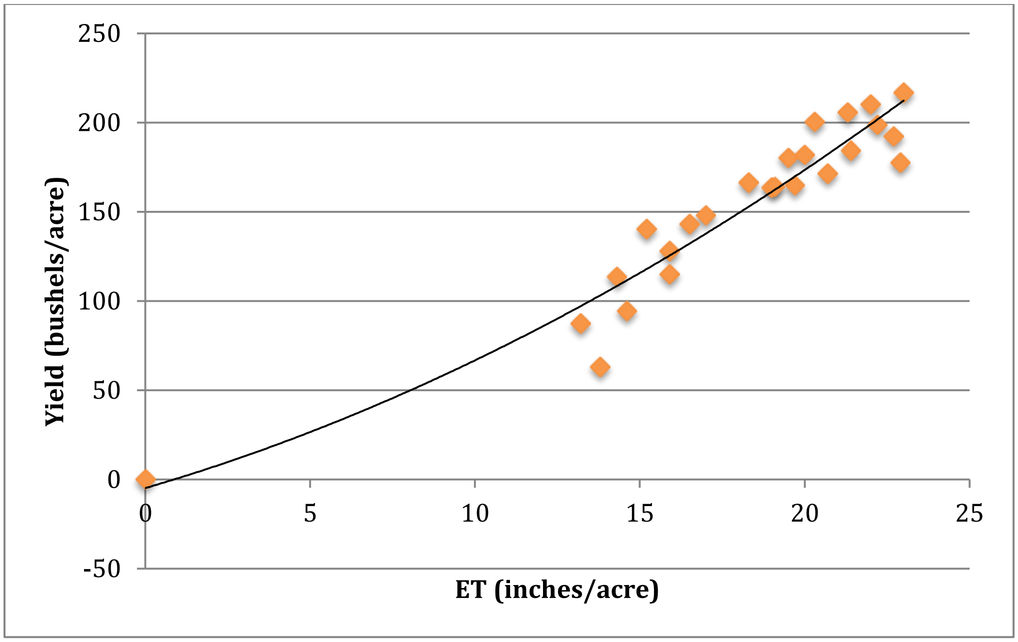

Figure A.2: Combined crop water production function for corn, 2008 – 2011

Table A.2: Combined production equation for corn, 2008 – 2011

CROP	PROFIT EQUATIONS	R^2 VALUE
CORN	$\pi = 0.1756w^2 + 5.403w - 4.8783$	0.91

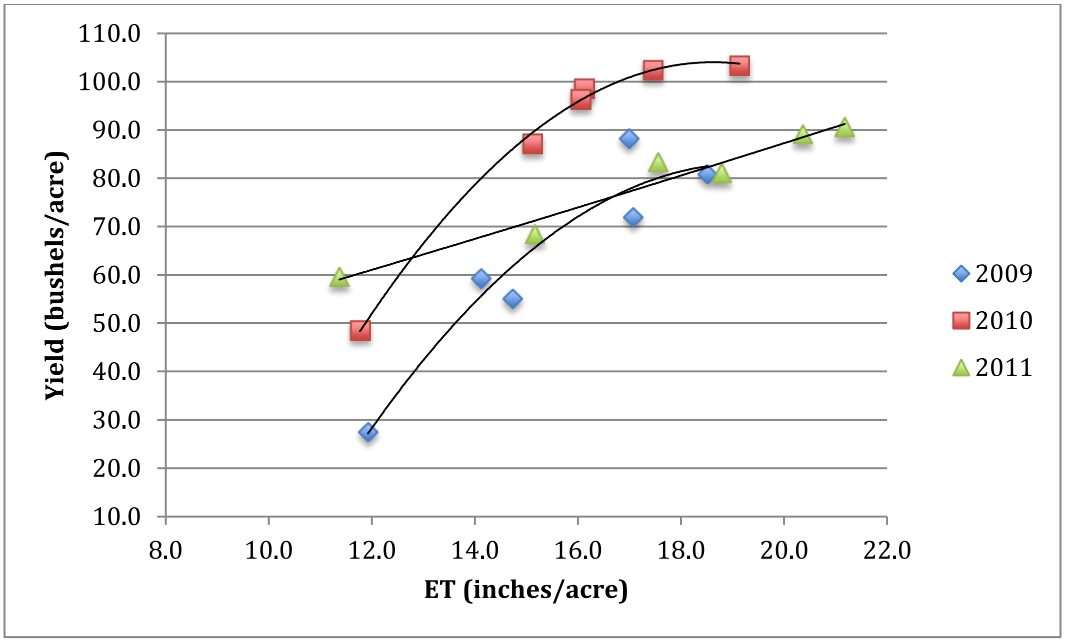

Figure A.3: Water production functions for wheat, 2009 – 2011

Table A.3: Production equations for wheat, 2009 – 2011

WHEAT	PROFIT EQUATIONS	R^2 VALUE
2009	$\pi = -1.043w^2 + 40.153w - 303.4$	0.91
2010	$\pi = -1.1865w^2 + 44.195w - 307.51$	0.99
2011	$\pi = 0.012w^2 + 2.894w + 24.585$	0.96

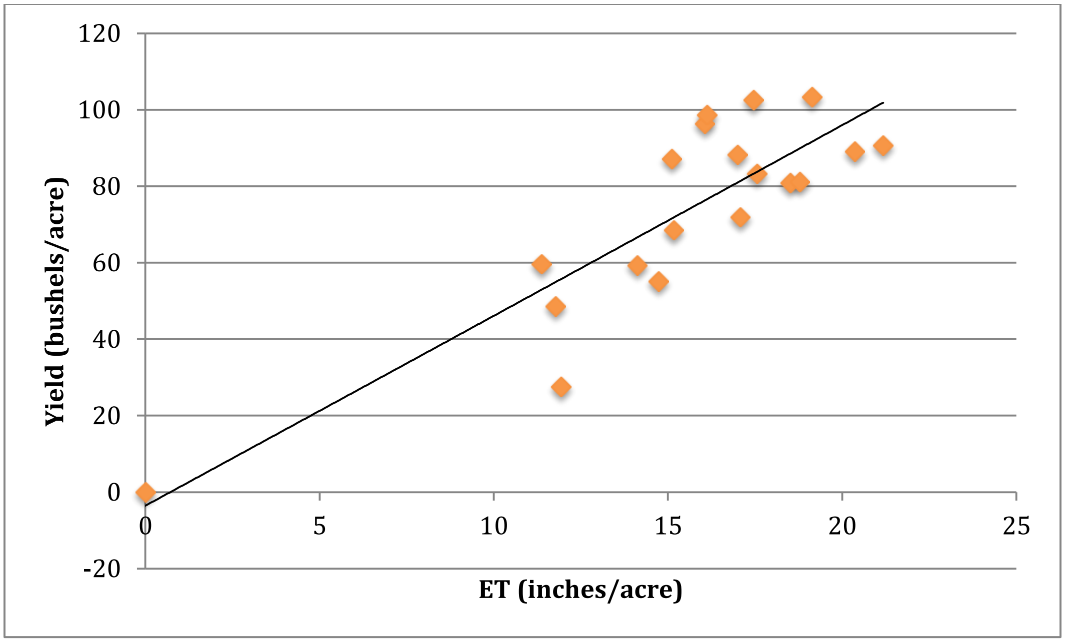

Figure A.4: Combined crop water production function for wheat, 2009 – 2011

Table A.4: Combined production equation for wheat, 2009 – 2011

CROP	PROFIT EQUATIONS	R^2 VALUE
WHEAT	$\pi = 0.0011w^2 + 4.9547w - 3.5512$	0.75

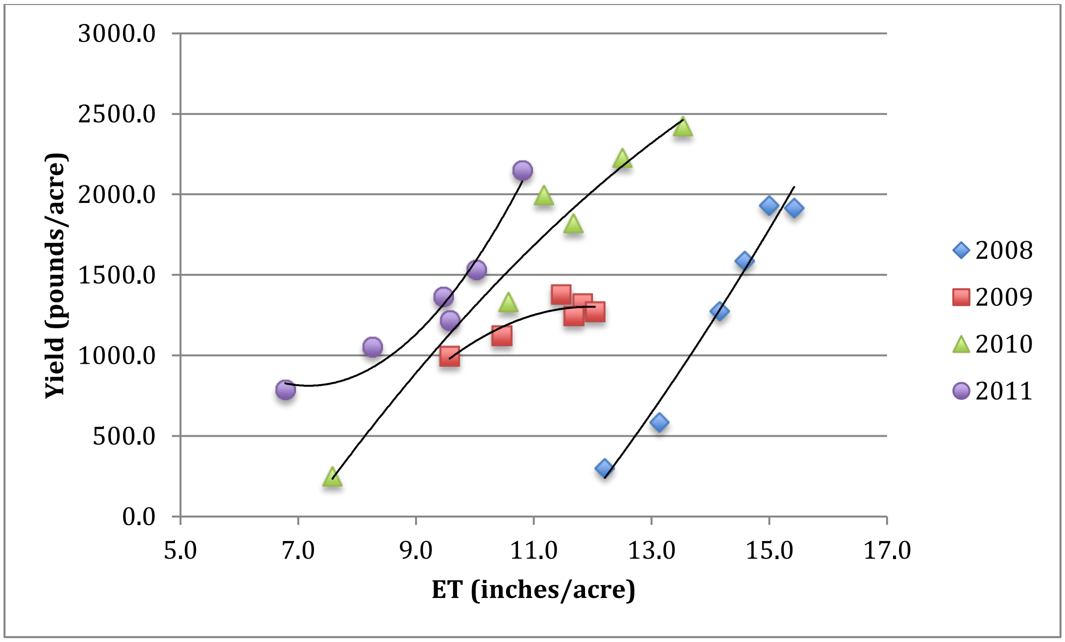

Figure A.5: Water production functions for beans, 2008 – 2011

Table A.5: Production equations for beans, 2008 – 2011

BEANS	PROFIT EQUATIONS	R^2 VALUE
2008	$\pi = 21.555w^2 - 33.354w - 2564.9$	0.97
2009	$\pi = -57.146w^2 + 1365.1w - 6850.3$	0.85
2010	$\pi = -19.451w^2 + 784.85w - 4597.3$	0.96
2011	$\pi = 96.226w^2 - 1380.9w + 5766.2$	0.95

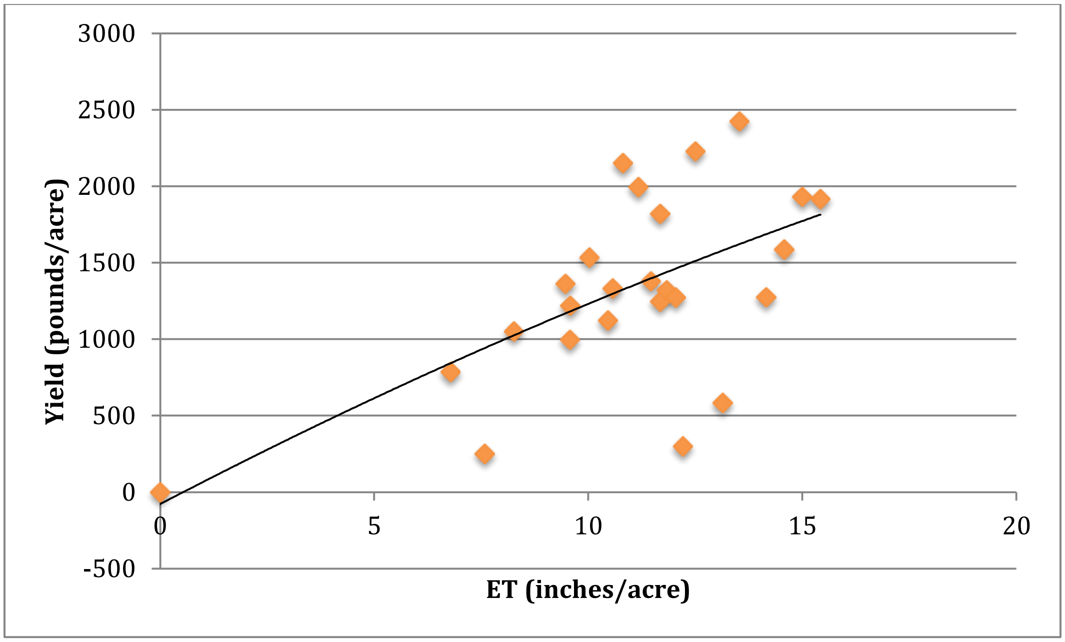

Figure A.6: Combined crop water production function for beans, 2008 – 2011

Table A.6: Combined production equation for beans, 2008 – 2011

	PROFIT EQUATIONS	**R^2 VALUE**
BEANS	$\pi = -1.5089w^2 + 146.03w - 78.339$	0.38

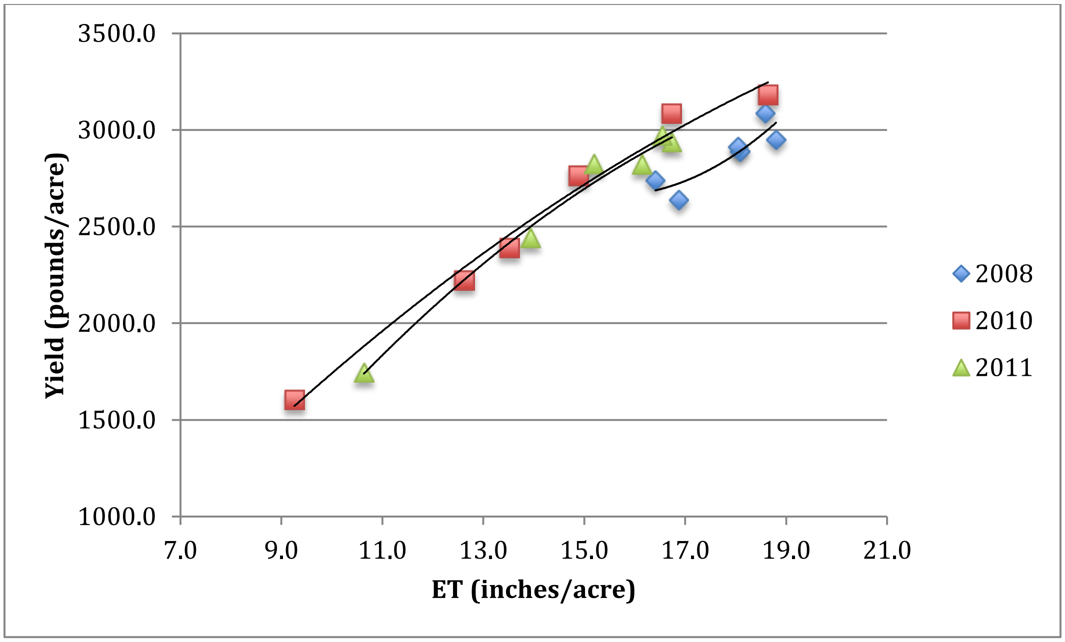

Figure A.7: Water production functions for sunflowers, 2008, 2010, 2011

Table A.7: Production equations for sunflowers, 2008, 2010, 2011

SUNFLOWERS	PROFIT EQUATIONS	R^2 VALUE
2008	$\pi = 35.571w^2 - 1105.7w + 11254$	0.78
2010	$\pi = -5.7903w^2 + 340.05w - 1080.8$	0.98
2011	$\pi = -10.744w^2 + 494.5w - 2305.4$	0.98

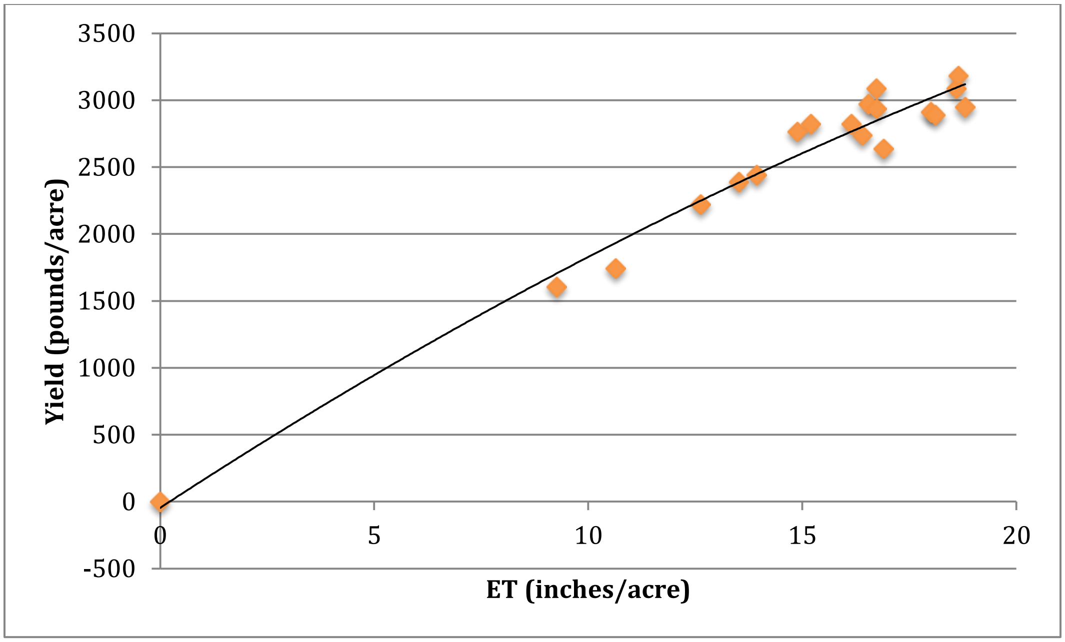

Figure A.8: Combined crop water production functions for sunflowers, 2008, 10, 11

Table A.8: Combined production equation for sunflowers, 2008, 2010, 2011

	PROFIT EQUATIONS	R^2 VALUE
SUNFLOWERS	$\pi = -2.1686w^2 + 209.16w - 45.957$	0.97

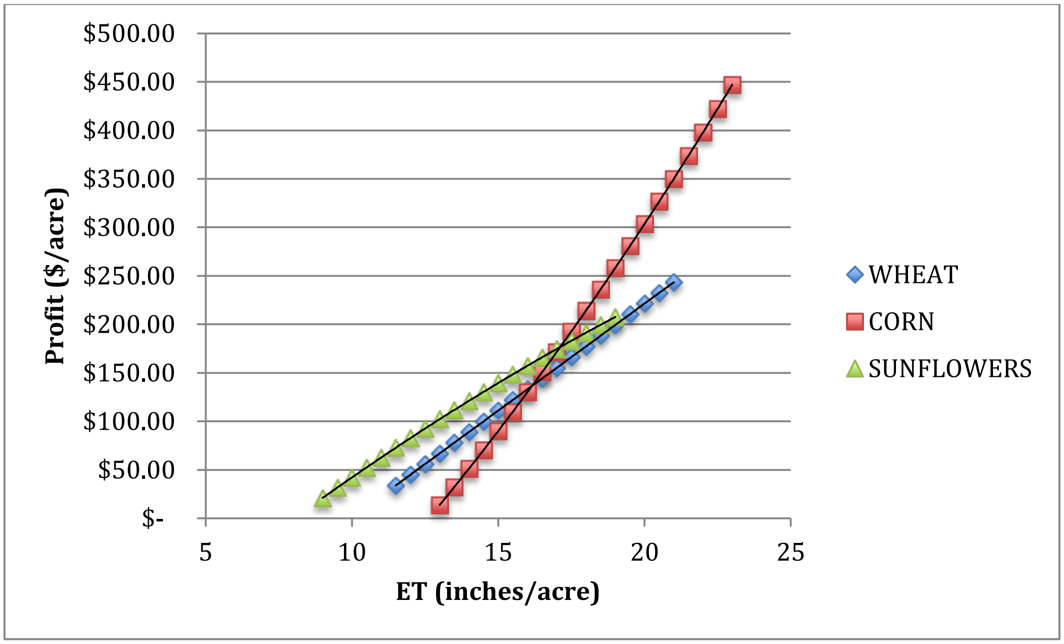

Figure A.9: Profit functions using combined production functions, 2010 prices

Table A.9: Profit equations for combined production functions, 2010 prices

CROP	PROFIT EQUATIONS	R^2 VALUE
WHEAT	$\pi = 0.0049w^2 + 21.899w - 218.53$	1
CORN	$\pi = 0.6487w^2 + 19.984w - 355.64$	1
SUNFLOWERS	$\pi = -0.2725w^2 + 26.281w - 193.41$	1