THESIS

COMPARATIVE PROFITABILITY OF IRRIGATED CROPPING ACTIVITIES FOR TEMPORARY WATER TRANSFERS

Submitted by

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ABSTRACT

COMPARATIVE PROFITABILITY OF IRRIGATED CROPPING ACTIVITIES FOR TEMPORARY WATER TRANSFERS

In response to a projected gap in water supply and demand, Colorado's Water Plan calls for up to 50,000 acre-feet of temporary water transfers from agricultural to municipal and industrial uses by 2030. Water stakeholders, however, want to avoid buy and dry scenarios, implying that a portion of agricultural water-right holders' consumptive use (CU) should remain available for on-farm agricultural production. Alternative Transfer Methods (ATMs) represent the regulatory mechanisms that enable temporary water transfers without permanent drying of agricultural land. To participate in an ATM, water-right holders must first establish a historical consumptive use (HCU) baseline which can then be allocated to agricultural production or temporary transfer. When faced with less water, producers may pursue several management options, including: rotational fallow, deficit irrigation, changes to crop mix, or changes to other practices like harvest timing. Yet, previous research on the risk profile of these options and their effect on producers' expected adaptation behavior is limited. This research develops a framework to compare the expected profitability of irrigated cropping activities, and in doing so, accounts for differences in risk and water-leasing potential. The framework is applied to a case study of twelve selected irrigated cropping activities on a well-drained silt loam soil in northeastern Colorado using stochastic enterprise analysis. Specifically, we compare gross margins for two corn (grain and silage) and two alfalfa (two cut and three cut) cropping enterprises on a per water-unit basis (one unit equals 12.94 acre-inches of CU); each under full irrigation, deficit irrigation, and partial fallow water management strategies. First, we simulate producers' expectations about gross margins based on empirical distributions of precipitation, price, and cost data for 1992 – 2017 and the FAO crop water production function. Second, we employ econometric analysis of the first, second, and third moments of the simulated gross margin distributions to estimate a risk premium for each activity. Fully-irrigated corn is set as the reference activity (one acre requires 1 water-unit of irrigation or 12.94 acre-inches of CU) and we find that crop choice, harvest timing, and deficit/fallow strategies all significantly affect producers' risk exposure relative to the reference activity. Activities remaining in the efficient set are primarily the rotational fallow strategies which would enable 3.24 – 7.14 acre-feet of CU to be leased for every twelve water-units of their HCU baseline enrolled in an ATM at a breakeven cost of $ 386.05 to $ 791.51 per acre-foot. More land could be maintained in agricultural production for an identical amount of transferable water under deficit irrigation, but it would typically come at a higher breakeven cost of $381.95 to $850.19 per acre foot depending on the producers' choice of crop and harvest strategies. The results should be of interest to academic, producer, and policy audiences, respectively, as they provide insight on (i) a novel methodology for comparing irrigated cropping activities that incorporates expected profitability, risk, and leasable water into a single metric, (ii) a ranking of potential adaptation strategies for producers who participate in ATMs, and (iii) insight into the economic tradeoffs between maintaining agricultural working land while also allowing for temporary water transfers to other beneficial uses.

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DEDICATION

To Mom and Dad for fostering my curious nature.

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CHAPTER 1 – INTRODUCTION

Water is a scarce resource in many parts of the western United States and, as populations continue to increase, demand for this resource is expected to rise even further. As communities grow, one way that they can augment their water supplies is to purchase water rights from the agricultural sector. Permanent transfers of water can be attractive to the water right holder and buyer of the water right, but these transfers may be detrimental to rural economies—and impose a 'social cost'—if less and less cash ends up circulating through local communities and they are able to support fewer and fewer businesses. Colorado's Water Plan (2015) estimates that Colorado may lose 700,000 acres of irrigated agricultural land if the state does not implement market-competitive alternatives to permanent water transfers (State of Colorado, 2015). These market-competitive alternatives are referred to as alternative transfer methods (ATMs). ATMs vary in design, but their goal is consistent: allow for temporary transfers of water from agricultural users to municipal water users but keep agricultural land in production in the long run.

Colorado has set a policy goal of 50,000 acre-feet of ATM projects in play by 2030 (State of Colorado, 2015). However, there are obstacles that currently limit the adoption of ATMs (Brown and Caldwell, 2011). Costs and the uncertainty surrounding ATMs are primary deterrents, but given that some of these challenges are overcome, additional information gaps exist about how agricultural water rights holders will adapt their production practices in response to participating in these alternative transfer programs. Stakeholder participation is critical to the success of ATMs. This research evaluates how voluntary water limitations impact agricultural producers' profits. Considering risk preferences, what cropping activities might a producer desire when participating in an ATM, and what would it cost to incentivize a producer to voluntarily participate in an ATM agreement?

This research focuses on the agricultural water right holders and how they might allocate their HCU. The literature review focuses on water laws in Colorado, water markets, use of crop models, and the risk in farm planning. A conceptual framework is provided to outline the scenario modeled and the producer's decision problem. The framework is applied to a case study of twelve selected irrigated cropping activities. The methods and data section describe the process of creating a stochastic simulation and estimating the gross margins for these twelve activities. Econometric and risk analysis methods are used to estimate the monetary costs of risk, following the frameworks of Antle (1987) and Chavas et al. (2009). Comparative breakeven analysis is used to solve for the price of the transferable water that would allow the farmer to be indifferent between (i) earning revenue from a water-limited cropping activity plus leasing water, and (ii) earning revenue from fully-irrigated cropping activities without leasing any transferable water. Results are presented from the simulation and a discussion follows. The information and methods from the research could be beneficial to parties interested in leasing water.

CHAPTER 2 – BACKGROUND

This chapter provides a literature review on Colorado's water laws related to water transfers, water markets and alternative transfers, crop-water production functions, and the role of risk in farm activity planning.

2.1 Colorado Water Law

Water is a scarce resource in Colorado and water laws were created in response to the competing demands for this resource. Mining was an early form of industry in Colorado and water was a critical input for mining operations (Jones & Cech, 2009). When water was diverted from streams for mining, it altered or eliminated stream flows. Ultimately, actions upstream created a negative externality on operations downstream. This created a need for a system that determined water allocation, resulting in Colorado's first water laws.

Colorado created a system of prior appropriation; a system characterized by the phrase "first in time and first in right." To establish priority in this system, water users must establish judicial recognition of their water right via a water court decree. A "water right" is defined by priority date, use, volume, and terms and conditions that prevent injury to others.

The priority date determines an individual's ability to access water in times of increased scarcity. Water rights established early on are referred to as senior and those that came later are junior. During a drought, those with junior water rights may have their use of water curtailed or stopped so those with senior rights may have their full allocation met.

Water rights differ from property rights in that they are a “usufructuary” right: a right to use but not to own the water. Water right holders who do not use their right can lose it. A usufructuary right in combination with prior appropriation creates poor incentives for conservation and crop choice (Chong & Sunding, 2006).

Water rights can be bought and sold. Purchasing water rights is desirable because priority is retained with the transfer. The transaction requires going through court proceedings with the court examining any change in use of the water right, change in the place of use or point of diversion from the original water right (Jones and Cech 2009). The water court must determine that the water will be put to “beneficial use”, but the concept of “beneficial use” lacks strict definition (Howe, Lazo, & Weber, 1990). As part of the proceedings, the historical consumptive use (HCU) of the original water user is quantified. The objective of this HCU analysis is to find how much water was consumptively used and how did return flows accrue. HCU is measured over a representative time, sometimes as short as 18 years but usually at least 50 years (Jones and Cech 2009). Return flows are considered to limit negative externalities on downstream users; negative externalities from transfers could include a reduction in water quality or availability (Howe et al., 1990). The transaction is contingent on requiring water to be returned to the river in time, place, and amount so that downstream users are not negatively affected. Water rights holders can go to water court to change their use, but such change may not harm other water users’ rights.

Changing the use of water in Colorado is expensive in time and money. Alternative Transfer Methods (ATMs) attempt to lower the transactions costs related to transfers potentially reducing the incentive for buy and dry scenarios (Jones & Cech, 2009). The maximum transferable amount may not exceed the HCU.

2.2 Water Markets

Water markets are considered a solution to water scarcity issues. Much of the water withdrawn in Colorado is used for irrigated agriculture, generating low returns for that water (Howe & Goemans, 2003). The price of water is not determined in markets, and so the price does not reflect its scarcity (Olmstead, 2010). This in combination with Colorado's water laws does not create an incentive for producers to reduce the amount of water used for their operations.

The advantage of a water market is that water would be more efficiently allocated and used as an input that generates higher benefits; water would be transferred from low value uses to high value uses. However, this reallocation is not without controversy as water would be removed from agriculture and transferred to municipalities.

Transferring water impacts third parties not involved in the transaction because of the interdependency for water users. There are both positive and negative aspects to a transfer. A transfer of water may increase in-stream flow or water quality for those downstream of a recipient, a positive externality (Howe et al., 1990). However, a transfer can reduce water quality, water availability, and instream values for water near the origin of the transfer, a negative externality (Howe et al., 1990). Also, when water is transferred from agricultural to municipal users, uncompensated losses may result. The economic and social conditions of a river basin affect the impact of an agriculture to urban water transfer (Howe & Goemans, 2003). Agriculture is a source of income for a region. When that source is removed, the related, supporting businesses in the area may be hurt by loss of revenue.

Water markets are not naturally competitive. Water rights are not a homogenous product. Water rights with a more senior priority date are more desirable for municipalities and buyers are willing to pay more for water with a senior priority (B. G. Colby, Crandall, & Bush, 1993). Water markets do not have many buyers and sellers. In regional water markets, there may be only one or two large buyers who purchase water from a small number of water rights (B. G. Colby et al., 1993). The markets lack complete information and there are barriers to entry. There are costs to build and move water. Physical structures are required to facilitate the transfer of water from buyer to seller. Lack of a delivery system is a constraint on obtaining water from downstream users and to build a system is costly (Brown and Caldwell, 2011). A HCU analysis is needed to be able to transfer the water and this has a cost. Additionally, there are search costs and legal costs related to creating and enforcing contracts costs for buyers and sellers (Olmstead, 2010). A necessary condition that is needed to facilitate a transfer is that value gained from the water transfer must exceed the costs to execute the transfer (Taylor & Young, 1995). With high costs to facilitate a transfer, buyers and sellers may not be interested in a temporary agreement.

Satisfactory water markets are possible by making the market more competitive. The Northern Colorado Water Conservancy District (NCWCD) is an unusually effective water market (Hadjigeorgalis, 2009). Its shares are transferable, and homogenous. There is no responsibility for return flow. Temporary transfers only have to be approved by the board rather than the water court (Howe & Goemans, 2003). The homogenous nature makes NCWCD shares easier to trade and avoidance of water court lowers the transaction costs. Buyers and sellers are more informed through the use of spot water and bulletin board markets (Hadjigeorgalis, 2009).

Farmers historically have had limited courses of action for their water rights: continue farming with their allocated water, sell their rights to another farmer or sell their rights to municipal and industrial (M&I) users on a permanent basis. A newer option that has generated interest are alternative transfers. With ATMs, farmers can continue with irrigated crop production but can sell part or lease part of their water right on a temporary basis. An ATM transfers water from agriculture for a set duration, but ownership of the water rights remains with the original water right holder, the agricultural producer. Temporary transfers can avoid some of the political and local economic costs associated with permanent sale of water rights by farmers (B. Colby, Frisvold, & Mealy, 2015). ATMs may have a place in water markets because they have potential to reduce the externalities with transfers but also lower transaction cost, potentially adding more flexibility to water markets in Colorado.

ATMs will only be successful if there is stakeholder acceptance and participation (Brown and Caldwell, 2011). Those interested in temporary transfers would benefit from understanding of price ranges and terms that would incentivize the other party. Water right holders need to be compensated for forgoing the opportunity to fully irrigate crops. Income from ATM needs to be greater than or equal to the lost revenue by not being able to plant or fully irrigate crops. Pritchett et al. 2008 surveyed the South Platte Basin and respondents had a favorable view of the impact that leases would have. Survey responders stated preference to forgo irrigation was within the range of $225 to $575 per acre (Pritchett, Thorvaldson, & Frasier, 2008).

Relying on ATMs entirely for water would increase intermittency of the water supply. Alternative transfers are unlikely to replace permanent transfers entirely (McLane & Dingess, 2013). However, alternative transfers could be valuable by providing the fringe supply, providing water to municipalities and industry in years when there is an expected shortage. In years of surplus, the water is used for irrigated agriculture. These temporary transfers could be attractive to farmers wanting to remain in production and diversify their sources of income.

Currently, ATMs are limited in practice. The largest factor inhibiting temporary alternative transfer arrangements in Colorado are still high transactional costs (Brown and Caldwell, 2011), and a lack of the necessary legal framework to successfully implement them (McLane & Dingess, 2013).

Deficit Irrigation (DI) is an irrigation strategy that may benefit producers in regions where water is a limiting input; it is considered a potential option for an alternative transfer. There is extensive agronomic literature evaluating crop yield response to limited water. In the economic literature, DI is often an optimization strategy to maximize water productivity; this can be done by satisfying water requirements during drought-sensitive stages and reducing or withholding water during drought tolerant growth stages (Geerts & Raes, 2009). DI may not be economically viable. Manning et al. (2017) finds that it is only optimal for corn within a specific price range, and producers would do better reducing the planted acreage.

The ability to administer an ATM presents challenges that determine the feasibility of the ATM. Rotational fallowing will likely be easier to monitor through use of satellite imagery or visiting the site and observing that no crops were grown (Brown and Caldwell, 2011). Deficit irrigation has potential use in transfers in the future, but there is uncertainty around how to administer a deficit irrigation plan to ensure a reduction in consumptive use (Brown and Caldwell, 2011).

Alternative cropping is a method that involves changing the types of crops that are grown on the land to a crop that reduces consumptive use. Alternative cropping is an untested method, and like deficit irrigation, there may be legal and administrative hurdles that would need to be resolved before this method can be implemented to free up water for alternative transfers (Brown and Caldwell, 2011).

2.3 Crop Water Production Functions

Field trials collect valuable data that can be used to create crop water production functions. These functions show the relationship between yield and water. Water is often presented as either water applied or transpired in these functions. A benefit of using water applied is that the producer has direct control over this variable. Water transpired is the amount of water that the plant uses and that evaporates during the growing process; water transpired and evaporated from soil or evapotranspiration (ET) is a better predictor of growth and yield than applied water (Vaux & Pruitt, 1983). A production function from field trials is not universally applicable; a crop water production function will vary among crop types, but within a crop type, production functions can vary due to regional differences in growing season, climate, and other environmental factors (Igbadun, Tarimo, Salim, & Mahoo, 2007).

Field trials are time and labor intensive. Mathematical crop models, however, provide a more cost-efficient alternative. The main category of mathematical models for simulating crop-water production function are crop coefficient models and process-based crop growth models (Foster & Brozović 2018). There is not one crop model that is best for all uses (Boote, Jones, & Pickering, 1996). Crop coefficient models are beneficial because of their low data requirement and the ability to estimate crop yield response to water. The downside is that water deficits have identical impacts on crop yield irrespective of the timing of deficits.

Production functions that use relative ET as an exogenous variable allow for some site transferability. One of these generalized functions is the FAO's original water production function (Doorenbos and Kassam, 1979); this model has been popular among economists and engineers (Steduto & Food and Agriculture Organization of the United Nations, 2012). This function is still useful for first approximation related to water limitations and has been an input in economic models dealing with water allocation. The function is still used by researchers at the field scale (Yacoubi et al., 2010) and with decision support systems (Gastélum, Valdés, & Stewart, 2009).

2.4 Farm Planning: Profitability, Risk, and Tradeoffs

Farmers' decisions early in the year and throughout the growing season impact his possible returns at the end of the year. Producers plant, irrigate, and harvest crops under limited and stochastic irrigation deliveries and precipitation (Taylor & Young, 1995). There are risks associated with farming such as differences in expected returns for crops, variations in yields due to limited water, variable weather, and pests. Risks should be included in models because they better represent the decisions that agricultural producers face (Antle, 1983). Previous literature has examined risk and its influence on agricultural production (Dillon &

Scandizzo, 1978), (Chavas & Holt, 1996), (Hardaker, 2004). Farmers are risk averse; they are willing to forgo higher profits to mitigate risk. Specifically, farmers exhibit downside risk aversion (Chavas & Holt, 1996) and data supports assumptions of constant relative risk aversion (Pope & Just, 1991).

Crop choice can be a strategy that helps producers mitigate risk related to limited water. Although alfalfa has a higher water requirement than corn, it has properties that may make it preferable to corn when water is limited. Alfalfa growth stages are not particularly sensitive to stress (Downey, 1972). Corn, however, has growth stages that are sensitive to stress, especially during tasseling or pollination (Robins & Domingo, 1953). Partial seasonal irrigation for alfalfa could be a source of water-savings (Lindenmayer, Hansen, Brummer, & Pritchett, 2011). Alfalfa has deep rooting and drought induced dormancy. This allows alfalfa to suffer minimal stand loss when water is limited (Lindenmayer et al., 2011). Due to its resilience, deficit irrigating alfalfa is a possibility to supply water to water stressed areas (Hanson, Putnam, & Snyder, 2007). Using a dynamic programming model for a farm with uncertain water supplies, Taylor and Young (1995) found that a farm with options to plant corn, alfalfa, and sorghum, the optimal solution was for the crop portfolio to be dominated by alfalfa.

CHAPTER 3 – CONCEPTUAL FRAMEWORK

We consider the case of an agricultural water rights holder (the "producer") who has obtained a change of use designation for their water rights and is eligible to temporarily lease water for alternative beneficial uses outside of agriculture. To lease water in a given year, the producer may choose to voluntarily enroll all or part of their historical consumptive use (HCU) in an ATM program, under the assumption that temporary transfers can occur only occasionally over extended periods. The producer has three general options for allocating the HCU in years that they elect to lease water. First, they may maintain the status quo and decide to allocate all HCU (denoted $\overline{W}$) towards agricultural production ($\overline{W} = W_A$). Second, they may lease all the water to municipalities and industry ($\overline{W} = W_T$). Third, they may lease part of the HCU while implementing a water-limited cropping strategy with the remaining amount of their HCU ($\overline{W} = W_A + W_T$, where $W_A > 0$ and $W_T > 0$).

3.1 The Producer's Decision Problem

The producer's decision problem is to select an irrigated cropping activity to maximize expected utility E[U] subject to $\overline{W}$. The set of feasible irrigated cropping activities from which a producer may choose is denoted a_{ijk} where the *ijk* subscripts represent distinct crop (i), harvest (j), and irrigation (k) strategies, respectively, over which the producer exerts management control. As a pre-condition of enrolling in an ATM, we assume that these strategies are determined at the beginning of each growing season and fixed afterwards.

The producer, when choosing among strategies, will choose those for which the joint activity results in the highest utility. The producer is indifferent between two strategies if the utility from them are the same. Within this context, the preferred irrigated cropping activity is denoted

$$D_{ni} = \begin{cases} 1 & \text{if } E\left[U\left(\pi_{ijk}^{a}\right)\right] \geq \ E\left[U\left(\pi_{ijk}^{b}\right)\right] \quad \forall\, b\ \neq a \text{ and } ijk \text{ combinations} \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

We assume that producers are risk averse and that producer's risk preferences are represented by,

$$E\left[U\left(\pi_{ijk}^{a}\right)\right] = \ \ln \pi_A(W_A) + \pi_T(W_T) \tag{2}$$

where

$$\pi = \pi_A(W_A) + \theta\pi_T(W_T) \tag{3}$$

$$\overline{W} = W_A + W_T \tag{4}$$

$$\overline{W} = g(\pi_A, \pi_T) \tag{5}$$

such that the production technology implies a joint-product relationship arises from decisions over how to allocate the fixed input bundle W. Specifically, each allocation implies the production of outputs π_A and π_T that represent the gross margin from crop production and the gross margin from leasing agricultural water. Risk averse preferences over the returns to agricultural production by the logarithmic component of the utility function that satisfy the following condition:

$$\partial U/\partial\pi_A \ > \ 0 \ and\ \partial^2 U/\partial\pi_A^2 \ < 0 \tag{6}$$

The first derivative with respect to profits is positive, meaning the producer's utility increases as profit increases. However, the second derivative with respect to profits is negative meaning that the producer's utility is increasing at a decreasing rate as profit increases. The second condition is that utility decreases as profits increase. A characteristic of the logarithmic utility function is that it exhibits constant relative risk aversion (CRRA) and has an Arrow-Pratt relative risk aversion equal to 1.

$$\frac{\partial U^2/\partial \pi_A^2}{\partial U/\partial \pi_A}\pi_A = 1 \tag{7}$$

CRRA preferences are often used in economics and are representative of many decision makers' preferences (Chavas et al. 2009). The CRRA of 1 are consistent for a decision maker who is moderately risk averse as well as downside risk averse.

3.2 Risk Implications

As shown below, the logarithmic component of producers' utility that represents profits from agricultural production can be re-expressed in terms of risk-adjusted certainty equivalents (CEs) such that expected utility maximization simplifies to expected profit maximization under risk—implying that CEs and expected revenue from water leasing are additive. Because reducing irrigation on a farm may impact risk, we incorporate risk exposure into our economic analysis of the return to different cropping activities. Each cropping activity is associated with inputs (x) that produce an output (y). There are also uncertain variables uncertain variables (ε) that can influence production. We evaluate the moments of profit distributions to incorporate risk. The first moment is the mean:

$$M(x,y) = E[\pi_A(x,y,\varepsilon)] \tag{8}$$

The mean is the expected value of the distribution of the agricultural profits from the cropping strategy. Cropping strategies can be ranked by expected value. However, two strategies may have similar expected profits but may differ substantially in risk. Ranking these cropping strategies with expected value as the sole criteria ignores producer's risk preferences. Risk exposure can be analyzed by looking at the second and higher moments. The second moment is the variance:

$$V(x,y) = E\{[\pi_A(x,y,\varepsilon)] - M(x,y)^2\} \tag{9}$$

Variance measures the absolute deviation from the mean, and a strategy that generates higher variance will imply greater risk exposure for the producer. A risk averse producer will find this undesirable reducing utility. Variance does not capture differences in risk. Variance from the mean return is treated the same. The producer would likely have different responses to low returns, returns below the expected value, and high returns, returns above the expected value. To account for these differences in risk, we find the third moment of the distribution. The third moment describes the skewness of the distribution:

$$S(x,y) = E\{[\pi_A(x,y,\varepsilon)] - M(x,y)^3\} \tag{10}$$

Skewness measures asymmetry of the distribution. Cropping strategies with negative skewness implies the function is skewed left and positive skewness implies the function is skewed right. Negative skewness means that the strategy's distribution function has a greater exposure to low profit outcomes. Positive skewness would reflect that the strategy has a greater exposure to rewarding outcomes, profits above the mean. Downside risk averse producers are wanting to avoid a strategy or account for the skewness of returns in their preferences.

We rank cropping strategies using a certainty equivalent, a monetary measure that incorporates the mean, risk, and variance of the returns into a single value.

$$CE = M - R \tag{11}$$

The certainty equivalent is the expected return (M) less the risk premium (R). The risk premium is derived from the log utility function. Risk premium is what the producer is willing to pay to avoid risk and is an economic evaluation of risk exposure. The certainty equivalent compares the performance of each strategy while accounting for risk.

We follow the conceptual approach of Antle (1987) to translate estimates of variance and skewness into a risk premium, the cost of risk. The risk premium is a monetary measure of what the producer is willing to pay to forgo risk and can be compared to expected return. Risk premium is approximated as the following:

$$R = 1/2\, r_2 V + 1/6 r_3 S \tag{12}$$

$$r_2 = -(\partial^2 U/\partial \pi_A^2)/(\partial U/\partial \pi_A) \tag{13}$$

$$r_3 = -(\partial^3 U/\partial \pi_A^3)/(\partial U/\partial \pi_A) \tag{14}$$

The Arrow-Pratt absolute risk aversion parameter is r_2 and the downside risk aversion parameter from Antle 1987 is r_3 . Under risk aversion, r_2 is positive; an increase in variance V increases the cost of risk. With the logarithmic utility function $r_2 = 1/\pi_A$ and $r_3 = -2/\pi_A^2$. Under downside risk aversion, r_3 is negative. Increases in skewness will reduce the risk aversion parameter because it reduces the downside risk. This framework allows for cropping activities to be ranked according to risk-adjusted average profits, or certainty equivalents (CE). However, it ignores the potential revenues from leasing water. Therefore, to consider both of these joint outputs we evaluate product transformation curves.

3.3 Product Transformation Curves & Further Interpretation

The product transformation frontier (PTF) shows how the producer can allocate their fixed HCU for different bundles of risk-adjusted agricultural profits and temporary water transfers. Efficient allocations will lie on the curve. The PTF shows the tradeoffs between agricultural production and the leasable water. To increase the amount of transferable water, the producer needs to give up agricultural profits; a reduction in water results in a reduced ability to grow crops all else equal. The producer will want to choose the cropping strategies that lie along the frontier. These cropping strategies will be the strategies that will allow him to allocate his HCU to get the efficient combinations of profits and leasable water from his operation.

One option to interpret the PTF is to determine the efficient set of irrigated cropping activities. An irrigated cropping strategy is in the efficient set if no other activity lies to the north or east of it when plotted with agricultural profit on the vertical axis and leasable water on the horizontal axis. A second option is to employ ‘breakeven analysis’ that compares enterprises and finds the value for temporary water transfers (W_T) that would be needed to make the producer indifferent between enterprises.

The breakeven condition is found by setting the expected utility between two activities (a ‘reference’ activity and an ‘alternative’ activity) equal

$$CE(Reference) = CE(Alternative) + BEP\ x\ W_T(Alternative) \tag{15}$$

where the reference CE is the cropping activity with the highest certainty equivalent; or the optimal cropping activity in absence of water transfers or ATMs. The alternative CE is a cropping activity that has water available for temporary transfer. BEP is the price producer would need to be compensated for the leasable water breakeven with the reference strategy. BEP is solved with the following equation:

$$BEP = [CE(Reference) - CE(Alternative)]\ /\ WT(Alternative) \tag{16}$$

The BEP is solved on a per acre-inch of water basis. It is interpreted as the producer's minimum willingness to accept for an acre-inch net transaction costs. If the producer is not at least compensated the amount that he could have earned if he used the water for farming, then he is not willing to lease water.

CHAPTER 4 – DATA AND METHODS

This section describes data and methods used in a case study of selected irrigated cropping activities for the northeastern or ‘South Platte’ region of Colorado. The case study consists of an analysis of stochastic gross margins based on actual precipitation, prices, and costs for twelve selected cropping activities over the period, 1992 to 2017. Results of the case study highlight how the selected systems would have performed under these conditions. Presentation of the data and methods is divided into four sections. The first section provides an overview of the selected cropping activities. The next section describes the process to simulate yields, which is then followed by the process for creating stochastic budgets of gross margins. The final section is a description of the econometric and risk analysis.

4.1 Selected Irrigated Cropping Activities in the South Platte Region of Colorado

Twelve cropping activities are considered in the analysis and presented in Table 1. These activities represent likely adaptations that producers may enact in the short run, in response to water leasing opportunities via ATMs and are described by the joint decision over crop (i), harvest (j), and irrigation (k) strategies. First, the producer can choose between two crops: corn or alfalfa. Second, each crop has associated with it a traditional and alternative harvest strategy. If they grow corn, they can either grow the corn for grain or for silage; if he chooses alfalfa, he can choose whether to plan to harvest three cuts or two cuts. Different harvest strategies reduce the amount of expected CU from crop production. Growing corn for silage reduces the expected CU as compared to corn grain and the two cut strategy likewise reduces the CU for alfalfa. Corn for silage utilizes the same daily ET as corn for grain but is typically harvested one month earlier therefore resulting in lower seasonal ET. Assuming three cuts are possible during the growing season for alfalfa, the two cut strategy reduces CU because the producer limits irrigation to the first two cuts.

Table 1. Description of Twelve Selected Irrigated Cropping Activities, South Platte Region Colorado a/

Irrigated Cropping Activity (ijk)	Crop (i)	Harvest (j)	Irrigation (k)	Allocation of Consumptive Use (CU) per Water Unit b/			Planted Area
				HCU baseline	E(CU) of Irrigation for Crop Production	CU Allocated to ATM Program c/	
				(acre-inches)	(acre-inches)	(acre-inches)	(acres)
C1	Corn	Grain	Full	12.94	12.94	0.00	1.00
C2	Corn	Grain	Limited	12.94	9.70	3.24	1.00
C3	Corn	Grain	R. Fallow	12.94	9.70	3.24	0.75
S1	Corn	Silage	Full	12.94	11.94	1.00	1.00
S2	Corn	Silage	Limited	12.94	8.95	3.99	1.00
S3	Corn	Silage	R. fallow	12.94	8.95	3.99	0.75
A1	Alfalfa	Three cuts	Full	12.94	12.94	0.00	0.48
A2	Alfalfa	Three cuts	Limited	12.94	9.70	3.24	0.48
A3	Alfalfa	Three cuts	R. fallow	12.94	9.70	3.24	0.36
T1	Alfalfa	Two cuts	Full	12.94	7.73	5.21	0.48
T2	Alfalfa	Two cuts	Limited	12.94	5.80	7.14	0.48
T3	Alfalfa	Two cuts	R. fallow	12.94	5.80	7.14	0.36
N1	None	n.a.	n.a.	12.94	0.00	12.94	0.00

a/ The selected scenarios represent a portfolio of likely adaptation practices that agricultural producers could potentially implement when faced with increased water scarcity for agricultural production as the result of temporary water leasing through an ATM.

b/ One water unit is defined as 12.94 acre-inches of CU (the expected irrigation requirement for one acre of corn grain to reach maximum ET). The total water units available on a given farm will equal their whole-farm water irrigation quota in acre-inch equivalents divided by 12.94 acre-inches.

c/ ATM = Alternative Transfer Method for temporary water lease from agriculture to an alternative beneficial use.

After choosing a planned harvest strategy, the producer chooses an irrigation strategy (denoted with subscript k). There are three options to consider: fully irrigated, limited, and a rotational fallow strategy. The fully irrigated strategy involves applying enough irrigation to meet the expected seasonal ET for the crop and harvest decision. The limited irrigation strategy is characterized by the producer reducing irrigation so that the amount of irrigation water consumptively used is 75% of the irrigation water consumptively used by the fully irrigated strategy for that crop_i and harvest_j. The rotational fallow strategy reduces acreage but fully irrigates the crop. The volume of irrigation water evapotranspired is the same for the limited irrigation and rotational fallow strategies for the same crop_i and $\text{harvest}_{j.}$

Different combinations of crop_i, harvest_j, and irrigation_k result in varying values of expected consumptive use, which we present in Table 1 in two ways. The reference case for the case study is fully irrigated corn for grain in the South Platte River Basin. First, the estimated seasonal CU of irrigation on a per acre basis for corn grown for grain is 12.94 inches of water—based on an estimated total ET for growing corn for grain near Greeley, Colorado equaling 23.9 inches (Schneekloth & Andales, 2017). The estimated seasonal CU of the water right on a per-acre basis for the other 11 irrigated cropping activities are also shown in the second column of Table 1. Water available for lease is obtained by adjusting the combination of crop_i, harvest_j, and irrigation_k strategies to reduce expected CU from crop production on a per water-unit basis, where one water unit is the reference case equivalent of 12.94.

We assume the producer's quantified HCU is equal to 12.94 acre-inches; the HCU is large enough that the producer can lease water or continue to plant a full acre of fully irrigated corn if he chooses to do so. If the CU of irrigation water is lower than 12.94 acre-inches, the assumed HCU, there is available water to temporarily transfer. Available water to lease is the difference between HCU and CU of irrigation water. Note that the limited and fully irrigated strategies for corn grain have the same area planted, but different E(CU) of irrigaton, for activity$_{ij}$. In contrast, the rotational fallow strategy achieves the same level of ET as that of the limited irrigation strategy by reducing the area planted. Table 2 illustrates how expected consumptive use for each irrigation activity is determined. For corn grain, 23.9 inches of water is the net crop water requirement (NCWR). The crop uses water from a few sources: the soil, precipitation, and applied irrigation. The available soil moisture (ASM) is 3.3 inches assuming a 3-foot root depth, a silt loam soil and 50% depletion (Schneekloth & Andales, 2017). Note the effective seasonal precipitation is different for corn and alfalfa because the crops have differing growing periods. Production for corn grain and silage is set from May to September; Alfalfa is set to April to August with the first cut occurring at the beginning of June, the second cut at the beginning of July, and the third at the beginning of August. The value reported in table 2 is the mean seasonal precipitation from CoAgMet weather stations listed in appendix table A1.

The producer has estimates for water that is available for lease. Historically, these agreements for temporary transfers like an Interruptible Water Supply Agreement are made before the growing season in March. The producer leases this water. However, if there is less precipitation than average during the growing season there are going to be larger impacts on the yield. If there is more precipitation than average, then the producer does not need to irrigate as much. We assume the producer does not have a spot market for water and cannot transfer water in real time, and so the producer must rely on expected values for the temporary water transfer.

Table 2. Crop Consumptive Use and Irrigation Requirements of the Twelve Selected Irrigated Cropping Activities a/

Irrigated Cropping Activity (ijk) b/	Crop Water Requirement	Sources of Crop Water Requirements			Planted Area	Total Irrigation	E(CU) from Crop Production
		Soil Water	E(Effective Precipitation)	Irrigation Water			
	in / ac	in / ac	in / ac	in /ac	ac	ac-in	ac-in
C1	23.90	3.30	7.66	12.94	1.00	12.94	23.90
C2	20.67	3.30	7.66	9.71	1.00	9.71	20.67
C3	23.90	3.30	7.66	12.94	0.75	9.71	17.93
S1	22.90	3.30	7.66	11.94	1.00	11.94	22.90
S2	19.65	3.30	7.66	8.96	1.00	8.96	19.92
S3	22.90	3.30	7.66	11.94	0.75	8.96	17.18
A1	37.10	3.30	7.04	26.76	0.48	12.94	17.94
A2	30.41	3.30	7.04	20.07	0.48	9.71	14.70
A3	37.10	3.30	7.04	26.76	0.36	9.71	13.45
T1	26.33	3.30	7.04	15.99	0.48	7.73	12.73
T2	22.33	3.30	7.04	11.99	0.48	5.80	10.80
T3	26.33	3.30	7.04	15.99	0.36	5.80	9.55

a/ Data are adapted from Schneekloth and Andales(2017) and representative of a field with silt loam soils with depth of 3 foot root zone

b/ See Table 1 for a more complete description of the irrigated cropping activities

The expected net irrigation requirement (NIR), the amount of applied irrigation that is consumptively used is obtained with the following:

$$E(NIR) = NCWR - ASM - E(AEP) \tag{17}$$

AEP is the average effective participation and is the mean of the seasonal precipitation over the growing period. NIR is less than the applied water because irrigation is not 100 percent efficient. If the irrigation efficiency (EFF) is assumed as 0.80, representative of a center pivot system, water applied would be approximately 16.18 inches. The values in Table 2 are initially presented in inches. To find the value in acre-inches, the values are multiplied by the area planted.

The amount of water that is actually used during the growing period for production, ET_{ijk}^{a}, is found using the following equation:

$$ET_{ijk}^{a} = NIR_{ijk} + ASM_{ij} + AEP_{ij} \tag{18}$$

NIR_{ijk} is assumed constant and applied optimally during the growing season. ASM_{ij} is constant. The crop uses all the acre-inches of water from the soil. Whether the crop's implied CU target is reached is dependent on the stochastic element, the seasonal effective precipitation, AEP_{ij}. The data for AEP comes from the Colorado Agricultural Meteorological Network (CoAgMET)("CoAgMET Homepage," n.d.). Precipitation data is used from multiple weather stations across Northeastern Colorado over multiple years from 1992 to 2017. Stations were added during this time and most stations do not have data spanning across the entire duration. There is a combination of 186 weather station-years. A table of station IDs and years used in the analysis is available in the appendix, table A1.

The limited irrigation and fallow strategy reduce the $E(NIR)$. The limited irrigation strategy is a strategy where the producer plans to reduce $E(NIR)$ by 25%. The reduction in $NCWR$ between the fully irrigated and limited irrigation strategy is equal to the reduction in $E(NIR)$. This reduction in CU is called the CU allocated to ATM program in Table 1. The rotational fallow strategy involves reducing the amount of land from the reference strategy by 25%. Both strategies reduce the $E(NIR)$ by 25% and have the same $E(NIR)$. However, the strategies will have different maximum yields and E(CU) from Crop Production. The reduced acreage strategy forgoes the available earnings from planting a quarter of an acre of land; this strategy has barren land. The E(CU) from Crop Production for rotational fallow is less than that of the limited irrigation strategy because we assume the precipitation and the soil moisture for the fallowed land is not consumed. The DI strategy reduces irrigation but if there are higher levels of precipitation than expected, the crop uses the water, which can result in positive benefits where yields are equal to the reference case.

Alfalfa has a higher NCWR than corn; the producer is limited by his HCU and is unable to grow a full acre of alfalfa. The estimated NCWR of alfalfa is 37.1 inches near Greeley, CO (Schneekloth & Andales, 2017). If the producer chooses to grow alfalfa, he needs to reduce the area planted from 1 acre to 0.36 acres to satisfy the HCU constraint. A full irrigation strategy over three cuts for alfalfa has no leasable water. This strategy has the same NCWR as the corn grain reference strategy. All limited irrigation strategies for alfalfa reduce the NCWR and create the possibility of an alternative transfer.

For two cut alfalfa, the farmer only applies irrigation during the first two cuts for alfalfa. Precipitation is higher during the earlier part of the season and less irrigation is needed for the earlier cuts. However, the alfalfa stand is still planted and consumptively uses water from the soil and precipitation even if the producer no longer is applying irrigation water during that last month. This water needs to be accounted for and is not available for lease.

4.2 Yield Data

Yields are simulated using the CoAgMet precipitation data and FAO original water production function (Doorenbos & Kassam, 1979). The production function is a crop coefficient model that relates relative yield reduction to ET. The equation is algebraically manipulated to estimate yields:

$$Y_a = Y_p - Y_p K_y (1 - \frac{ET_a}{ET_p}) \tag{19}$$

ET_a is the actual evapotranspiration and ET_p is the maximum evapotranspiration. Y_a is the achieved yield and Y_p is the maximum potential yield that corresponds with the maximum evapotranspiration. K_y is the seasonal crop coefficient. It captures the biological and physical processes that occur between water use and production (Steduto & Food and Agriculture Organization of the United Nations, 2012). When ET_a and ET_p are equal the producer's yields for that year equal the maximum yield possible for the area of planted land.

The seasonal crop coefficient (K_y) used for Alfalfa is 1.1 and 1.25 for corn (Steduto & Food and Agriculture Organization of the United Nations, 2012). A crop coefficient greater than 1 intuitively means a crop is more sensitive to water deficit; corn is more sensitive to a water deficit and has a greater reduction in yields in response to reductions in ET than alfalfa.

The max yield (Y_p) for corn is obtained using data from variety performance trials from 2007 by CSU Extension (*2007 Colorado Corn Variety Performance Trials*, 2008). The assumed max yield for a full acre of fully irrigated corn is 212.2 bushels and the assumed maximum yield for alfalfa is 7.48 tons for a full acre of alfalfa. 7.48 tons is the average yield from 2005. I used this value because the yield was closer to the estimated yields from the crop enterprise budgets from which the variable costs are based on. The 2007 trial had an alfalfa yield almost twice the reported yield from the enterprise budgets for alfalfa.

Values for maximum ET (ET_p) are from CSU extension (Schneekloth & Andales 2017). The value for the estimated seasonal water requirement (consumptive use) for Greeley Colorado is assumed as ET_p.

The crop production functions have a linear plateau constrained by the respective yield max, Y_p. The fully irrigated and limited irrigation strategy achieve the Y_p if that year's precipitation is greater than or equal to AEP. In years where precipitation is lower than AEP, the crop yield produced, Y_a, is less than Y_p. We assume that for the limited irrigation strategy that the maximum yield from the fully irrigated strategy is achievable. This assumption is made because the producer agrees to lease irrigation water, a variable he controls, with the expectation he will strain his crop in the spring. If precipitation is greater than AEP the crop consumes the available water. This event would be difficult to prevent without the ability to monitor ET for the crop in real time. In the model, we assume that this is unable to monitored and do not punish the producer for the unexpected rainfall. Like the other irrigation strategies, there is downside to production risk. If the actual precipitation on the farm is less than the expected value, there are additional reductions in yield.

Corn grain and silage is harvested one time at the end of their respective growing season. If there is more precipitation, then ET_a is capped and is set equal to ET_p. The yields from the simulations cannot generate values greater than Y_p. The corn simulations provide yields in bushels for corn grain and tons for silage.

Table 3. Simulated Yields for Selected Irrigated Cropping Strategies, South Platter Region, 1992 – 2017 (N = 2232)

Crop (i)	Harvest(j)	Irrigation (k)	Units	Mean	Variance	Skewness	Min	Max	C. Var
Corn	Grain	Full	bu/ac	197.64	377.20	-1.26	127.19	212.20	0.10
Corn	Grain	Limited	bu/ac	172.29	880.80	-0.32	91.28	212.20	0.17
Corn	Grain	Fallow	bu/ac	148.23	212.17	-1.26	95.39	159.15	0.10
Corn	Silage	Full	t/ac	25.20	6.73	-1.26	15.79	27.15	0.10
Corn	Silage	Limited	t/ac	22.13	15.12	-0.09	11.37	27.15	0.18
Corn	Silage	Fallow	t/ac	18.90	3.78	-1.26	11.85	20.36	0.10
Alfalfa	Three cuts	Full	t/ac	3.41	0.03	-0.88	2.87	3.57	0.05
Alfalfa	Three cuts	Limited	t/ac	2.85	0.12	0.31	2.17	3.57	0.12
Alfalfa	Three cuts	Fallow	t/ac	2.56	0.02	-0.88	2.16	2.68	0.05
Alfalfa	Two cuts	Full	t/ac	2.42	0.13	0.50	1.74	3.57	0.15
Alfalfa	Two cuts	Limited	t/ac	2.00	0.14	0.69	1.31	3.57	0.19
Alfalfa	Two cuts	Fallow	t/ac	2.74	0.08	0.50	1.30	2.68	0.15

a/ Data are from authors' simulation analysis using historical precipitation data (CoAgMet) and the original FAO Crop Water Production Function (Doorenbos and Kassam, 1979) calibrated to the South Platte Region.

b/ The total number of observations (N = 2232) is found by multiplying the number of observations per activity (Nijk = 186 for the ijk-th activity by the number of activities considered N = 186 x 12 = 2232).

To simulate silage yields, we follow the same procedure as estimating the yields for corn grain. Y_p for silage is found using 22.9 as the ET_a in the corn production function and then solving for Y_a. However, Y_a from the function is in bushels of corn while silage is sold in tons and is made from the whole corn stalk. Approximately 7 to 8 bushels equal one ton of silage (Blonde, n.d.) To get an estimate for silage produced, we multiply the bushels from the FAO function by 0.135 (Edwards & Hart, n.d.).

Alfalfa is simulated with the producer choosing to irrigate during the first two harvests or for all three. The expected ET for each cut is assumed the same proportion of the seasonal ET. Alfalfa has a higher NCWR than corn. The producer reduces the area planted so that the CU of irrigation for the alfalfa is the same as the CU irrigation for corn, roughly 0.48 acres.

More precipitation is expected during the earlier harvests and so less irrigation is needed for the earlier cuts. The farmer could achieve two full harvests and reduce the total irrigation by focusing on satisfying the NCWR for the first two cuts. However, the CU does not cease after the second cut; Alfalfa is a perennial. The alfalfa stand is still in the field where and continues to consume water. There is a yield during the last month for the two-harvest strategy with ET supplied from precipitation that last month.

The simulation of yields for the twelve cropping strategies, table 3, show yield distributions with positive and negative skewness. This is not unexpected due to how yields were modeled. The FAO crop production function uses a maximum yield. I assume that the producer can reach the maximum yield if the actual precipitation equals the expected precipitation. The variation in yields in the simulation are caused by the precipitation for that weather station-year being lower than the expected value, creating a negative skew. The exceptions in the data are crops where the maximum yield was not defined as a binding constraint: the two cut alfalfa and the limited irrigation strategy. In the model, more precipitation results in a higher ET which translates to higher yields.

The yield and variance values for grain are much larger in comparison to the other crops due to corn grain being measured in bushels while the other crops, silage and alfalfa, are measured in tons. However, the coefficient of variation is similar across the cropping activities.

4.3 Price and Cost Data

Colorado corn and alfalfa prices were obtained from the National Agricultural Statistics Service ("USDA - National Agricultural Statistics Service - Colorado - Current Annual Statistical Bulletins," 2018) for all years. Silage prices were also obtained from NASS but tracking silage prices ceased after 2009. University of Nebraska-Lincoln research shows that corn silage should be valued at 7.65 x the price per bushel of corn for a ton of corn silage that is harvested at 60%-65% moisture ("Corn Worth more as Silage or Grain," 2017). Prices for silage after 2009 were estimated using this equation. Appendix Table A3 shows the nominal price and variable costs used in the simulation.

Variable costs for corn are obtained from the USDA Economic Research Service from 2017 to 1996 using the costs for the region labeled as Prairie Gateway ("USDA ERS - Commodity Costs and Returns," n.d.). CSU Crop Enterprise budgets for irrigated corn in Northeastern Colorado were used for the years prior to 1996.

CSU crop enterprise budgets for Northeastern Colorado were used for variable costs for silage and alfalfa (“Agriculture & Business Management,” 2017). Crop enterprise budgets were not available for all years and all crops. If there were gaps, the first choice was to use an estimate of variable cost from CSU’s enterprise budgets for Northern Colorado. If a budget was not available for that year for Northeastern and Northern Colorado, the variable cost was assumed to be the same as the closest prior year with available data.

A change in the area planted reduces the variable costs; the variable costs are relative to an acre of planted land. For strategies that reduce acreage planted, the variable costs equal the planted area (less than 1) multiplied by the enterprise variable cost. Fixed costs in the CSU operating budgets are not included in the analysis because they will not vary by activity choices at the whole farm level.

Prices and variable costs are adjusted for inflation using an index of farm output from FRED (U.S. Bureau of Economic Analysis, 2019). Before adjusting the prices for inflation, the empirical data show a larger positive skew as one might expect. The prices are adjusted to 2017 real dollars.

Prices and cost data are summarized in Table 4. The data shows both positive and negative skew. Corn and silage show positive skew; the data is centered around a mean value with occasional years having higher prices and costs. The distribution of alfalfa prices and costs are negatively skewed. In the table, skewness is the standardized third moment. Comparing skewness, we see that the distribution of corn prices is the most skewed. Examining the data, corn prices were much higher than typical in 2011 and 2012. These high prices might be explained by drought conditions in Colorado and other states at the time leading to reduced supply of corn and higher prices. Silage prices are positively skewed but its distribution of costs show a larger skew. The distribution of alfalfa prices has a slight negative skew. Intuitively, a producer would want prices to have a positive skew and the costs negatively skewed.

Table 4. Output Prices and Variable Costs for Twelve Selected Irrigated Cropping Activities, South Platte Region, 1992 - 2017

	Units	Mean	Variance	Skewness	Min	Max	C. Var
Prices							
Corn	$/bu	3.59	0.35	0.96	2.74	4.92	0.17
Silage	$/ton	30.35	11.47	0.53	25.49	37.66	0.11
Alfalfa	$/ton	139.96	554.04	-0.03	95.83	175.93	0.17
Variable Costs							
Corn	$/acre	279.76	1160.32	0.09	220.60	337.24	0.12
Silage	$/acre	421.34	7092.75	0.67	304.21	581.06	0.20
Alfalfa	$/acre	409.33	8696.89	-0.37	226.73	560.95	0.23

4.4 Stochastic Budgeting of Gross Margins

A stochastic budget for gross margins is created for each of the irrigated cropping activities. Such simulations are helpful in analyzing hypotheticals about real systems, and stochastic simulation model can help make a systematic assessment of what may happen (Hardaker, 2004). We use @Risk an Excel add-in to perform a stochastic simulation of gross margins, where gross margins are calculated as,

$$GM_{ijk} = P_i \ x \ Y_{ijk} \ - \ VC_{ijk} \tag{20}$$

To perform the stochastic simulation, we defined the distributions of price, yield and variable costs as Johnson distributions. The analysis aims to know the values of the distribution parameters generated from the stochastic simulation, and so we do not want to arbitrarily select a continuous distributional form. However, techniques highlighted in Hahn and Shapiro (1967) describe how Johnson distributions have flexible form and a continuous distribution can be approximated using the parameters from the empirical distribution. @Risk has this programmed in and fits the Johnson distribution using the mean, standard deviation, skewness and kurtosis of the empirical data.

Once the distributions are defined, the program runs a Monte Carlo Simulation, randomly sampling from the distributions and creating a potential gross margin for each iteration. We ran a Monte Carlo simulation of 5000 iterations. By the law of large numbers, as we increase the number of iterations the sample of gross margins should approach the true underlying distributional form. The data from the Monte Carlo is used in the econometric and risk analysis.

4.5 Econometric Estimation

The econometric and risk analysis follows the framework of Chavas et al. (2009). There is anticipated heteroskedasticity. The regression coefficients are obtained with ordinary least squares, and the potential for heteroskedasticity is addressed with white standard errors. Equation 21 is used to estimate the gross margins of each cropping strategy. Equation 22 is used to estimate the variance and skewness of each cropping strategy where the superscript is $x = 2$ and $x = 3$, respectively

$$\begin{aligned}\pi_{ijk} = \beta_0 &+ \beta_1 Alfalfa + \beta_2 Harvest + \beta_3 Limited + \beta_4 RFallow \\ &+ \beta_5 AlfalfaLimited + \beta_6 AlfalfaRFallow \\ &+ \beta_7 Harvestlimited + \beta_8 HarvestAlfalfa \\ &+ \beta_9 HarvestAlfalfa + u_1\end{aligned} \tag{21}$$

$$\begin{aligned} u_1^x = \beta_0 + \beta_1 Alfalfa + \beta_2 Harvest + \beta_3 Limited + \beta_4 RFallow \\ + \beta_5 AlfalfaLimited + \beta_6 AlfalfaRFallow \\ + \beta_7 Harvestlimited + \beta_8 HarvestAlfalfa \\ + \beta_9 HarvestAlfalfa + u_x \end{aligned} \tag{22}$$

Due to there being three types of irrigation, two dummy variables are used to distinguish limited irrigation and fallow.

Using the coefficients from each regression, we estimate certainty equivalents (CEs). Risk variability (RV) is the cost for variance. A larger variance implies a wider distribution and more variation in returns. RV is calculated as is the risk skewness (RS) which is the cost of skewness. An increase in positive skewness decreases down-side risk exposure. A negative RS implies the returns are positively skewed for that cropping strategy. Risk premium (RP) is the sum of RV and RS. It is the cost that the producer is willing to pay to reduce the risk that and there is a decrease in downside risk exposure.

$$RV = \frac{1}{2} * \frac{1}{\pi} * V \tag{23}$$

V is the calculated variance from the gross margins, and π is the gross margin for the cropping activity.

$$RS = \frac{1}{6} * \frac{-2}{\pi^2} * S \tag{24}$$

S is the calculated skewness from the regression and π is again the gross margin for that cropping activity.

These values added together are the risk premium and this value is subtracted from the mean gross margin π for a cropping activity. The value obtained is the certainty equivalent, which can be used to rank the strategies based on producer risk preferences.

A comparative breakeven analysis is used to evaluate the price of agricultural water supplied to an ATM for the simulated farm using the certainty equivalents. The breakeven price can be used to gauge the feasibility of the producer participating in an ATM. We multiply the breakeven price by 12 in the results section and report value on a per acre-foot basis.

CHAPTER 5 – RESULTS AND DISCUSSION

Results and discussion are presented in three sections: econometric estimation of gross margin distributions for the twelve selected irrigated cropping activities, economic comparison of the gross margins of these activities under risk aversion, and tradeoff analysis comparing water available for lease to the estimated gross margins.

5.1 Econometric Estimation Results

Parameters are estimated using ordinary least squares (OLS) regression with White’s standard errors to correct for heteroskedasticity, results are in Table 5.

Table 5. Econometric Estimates of Mean, Variance, and Skewness of Returns using OLS with White's Standard Errors

VARIABLES	(1) Mean	(2) Variance	(3) Skewness
Alfalfa	-155.2***	-11,763***	-1.590e+06***
	(2.064)	(380.6)	(142,655)
Harvest	-91.16***	-162.8	-1.911e+06***
	(2.311)	(452.8)	(171,122)
Limited	-96.17***	1,803***	203,568
	(2.351)	(489.8)	(196,299)
RFallow	-109.8***	-9,207***	-925,148***
	(2.366)	(445.8)	(161,358)
AlfalfaLimited	22.63***	-1,016**	-37,265
	(2.296)	(421.7)	(158,366)
AlfalfaRFallow	42.71***	5,632***	879,077***
	(2.751)	(457.0)	(159,205)
HarvestLimited	10.02***	-2,643***	-184,487
	(2.375)	(448.9)	(171,241)
HarvestRFallow	29.44***	-465.7	-110,617
	(2.256)	(299.0)	(95,732)
HarvestAlfalfa	-42.15***	-41.77	2.127e+06***
	(2.304)	(427.8)	(162,516)
Constant	432.2***	20,542***	1.653e+06***
	(1.825)	(376.9)	(145,808)
Observations	60,000	60,000	60,000
R-squared	0.432	0.089	0.007

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

There are 5000 observations for each cropping activity obtained from the Monte Carlo simulation resulting in 60000 total observations. The reported F-test has a p-value of 0 for all regressions. The R^2 values are 0.432, 0.089, and .007 for the mean, variance, and skewness regression respectively. R^2 is likely low for the variance and skewness due to wide dispersion of values caused by squaring and cubing the residuals. A weighted least squares (WLS) regression could be used as well. Both OLS with White's standard errors and WLS with the correct weighting matrix obtain unbiased estimators.

With the yields, prices, and costs having varying direction and levels of skewness, the overall effect on the shape of the gross margins' distributions are ambiguous. The regression is composed of dummy variables that are used to identify each strategy. The first regression is how the parameters influence gross margins, the second how the parameters influence the variance of the gross margins, and the third how the parameters influence skewness. Note the gross margins are for an acre of land. Many parameters are found to be statistically significant for the three regressions. The reference activity for the regression is the corn grain, fully irrigated cropping activity, represented as the constant. More parameters are significant in reducing the variance of the gross margin than they are changing the skewness.

All variables are significant for the mean regression. Switching from corn to alfalfa, implementing a reduced irrigation strategy, or implementing an alternative harvest strategy changes the gross margins in comparison to the reference case. Having significant parameters for the variance and skewness regression, demonstrate that the producer's cropping decisions change the potential risk of his operation, and that risk should be considered when evaluating a cropping strategy.

The twelve cropping activities' gross margins, variance, and skewness are constructed from the coefficients. For example, the parameters relevant for the alfalfa, three cut, fallow activity are the estimates for crop variable, rotational fallow variable, and the interaction effect between the crop and fallow dummy variables. The relevant parameters for the corn silage limited irrigation activity are the harvest variable, deficit irrigation variable, and the interaction for harvest and deficit irrigation. From the regression the coefficient estimates for the alfalfa, three cut, fallow activity, are -155.2 for the crop, -109.8 for fallow, and 42.71 for the interaction effect, totaling -222.29. This value is the difference between the activity's gross margin and the reference activity's gross margin. Adding this value to the constant, I get the gross margin for the activity, $ 209.92. This process is done for each cropping activity, and then repeated to find the variance and skewness.

5.2 Economic Comparison under Risk Aversion

As shown in Table 6, cropping activities can be evaluated by their mean return, a measure that does not penalize for risk, and by their certainty equivalent, one which does. Table 6 includes estimated costs of variance and costs for skewness based off the assumption of risk averse preferences. The risk premium for each activity is dominated by the variance component, RV. Values for RS that are negative imply that the gross margin distribution has positive skew. This upside in potential gross margins reduces the downside related to the variance of the distribution. Growing corn for silage is the only strategy with gross margins with negative skew in the simulation. The activities with RS closer to 0 imply the distribution of gross margins is relatively symmetric.

Table 6. Risk Premium and Certainty Equivalent estimates for the gross margin of a simulated Northern Colorado Farm

Crop Activity a/	Mean Return ($)	Risk Premium ($)			Certainty Equivalent ($)
	(M)	Variance Component (RV)	Skewness Component (RS)	Total (RP = RV + RS)	CE = M - RP
C1	432.18	23.77	-2.95	20.82	411.36
C2	336.00	33.25	-5.48	27.77	308.23
C3	322.37	17.58	-2.33	15.25	307.13
S1	341.01	29.88	0.74	30.62	310.39
S2	254.86	38.33	1.22	39.56	215.31
S3	260.65	20.54	6.35	26.88	233.77
A1	277.01	15.85	-0.27	15.57	261.44
A2	203.47	23.51	-1.85	21.66	181.81
A3	209.92	12.39	-0.13	12.27	197.65
T1	143.70	29.83	-4.51	25.32	118.37
T2	80.18	41.90	-13.54	28.35	51.83
T3	106.05	21.37	-3.64	17.74	88.31

a/ See Table 1 for a more complete description of cropping activities

The ranking of strategies on agricultural returns, Figure 1, remains the same when we use mean or certainty equivalent. When we examine the means, certain strategies appear much more favorable than others due to having a much larger expected profit. This is reduced after adjusting for risk. For example, fully irrigated silage has a mean expected return that is roughly $5 and $19 higher than limited irrigated corn grain and rotational fallow corn grain respectively. When comparing the certainty equivalents, fully irrigated silage only has an expected return that is $2 and $3 higher than the limited irrigated and rotational fallow corn grain activities. Except for corn grain, the CE for each fallow strategy was superior to the limited irrigation strategy for each crop and harvest strategy. The ranking using CE, however, ignores the potential for revenue from temporary water transfers via enrollment in an ATM. Therefore, an alternative method of comparison that enables the evaluation of tradeoffs between potential revenues from agricultural production and water transfers is developed in the next section.

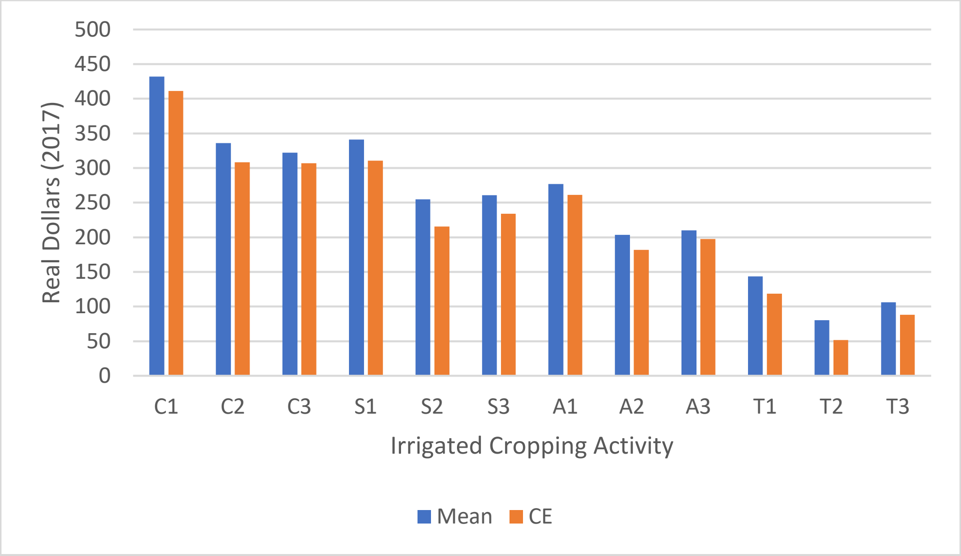

Figure 1. Comparison of Means and Certainty Equivalents of the Twelve Selected Cropping Activities

5.3 Tradeoff Analysis between Returns to Irrigated Cropping Activities and Available Water Transfers

Figure 2 shows the CE and the expected leasable water for each cropping activity. Activities more conducive to an ATM, from the producer's perspective, are those higher on the vertical axis and further to the right on the horizontal axis. A producer would want to implement one of these cropping activities because they are forgoing less in gross margins from agricultural production while having more transferable water. From Figure 2, we can identify an 'efficient set' of irrigated cropping activities that dominate the others. An activity is said to be in the efficient set if no other activity appears in the northeast quadrant relative to that activity.

If an activity *did* lie to the north and east, it would have a higher profit for an equivalent or greater quantity of leasable water and therefore be axiomatically preferable.

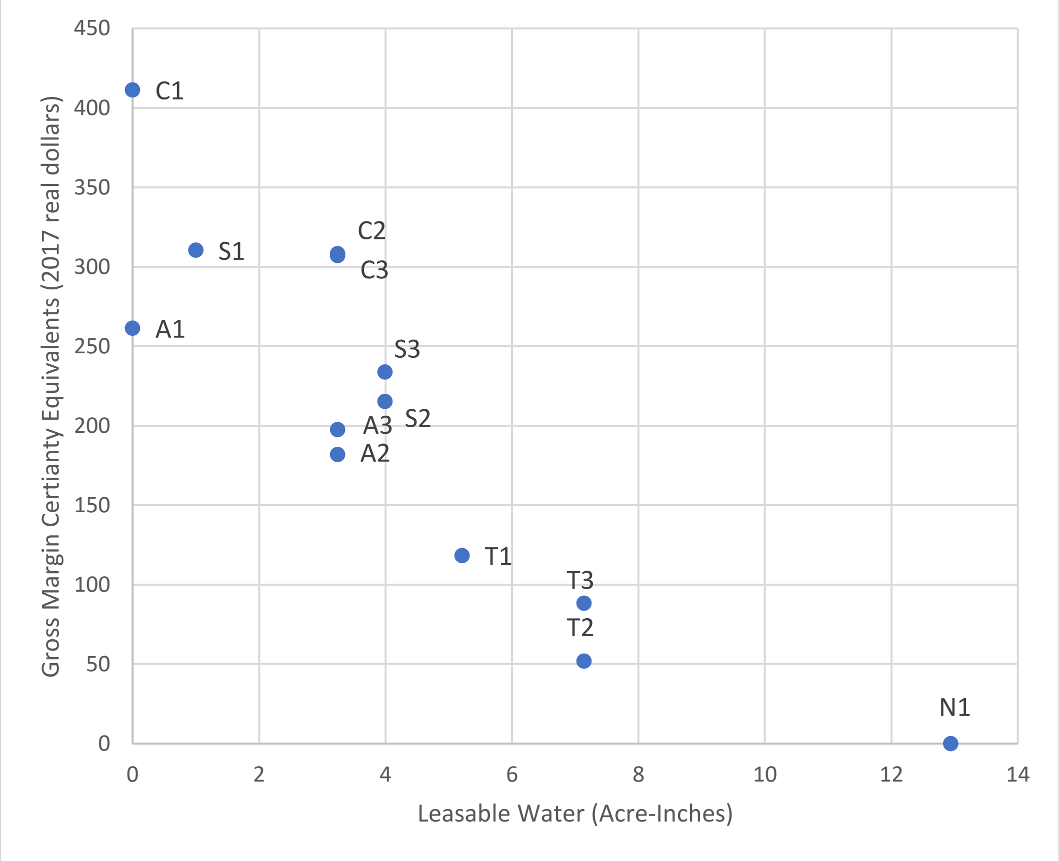

Figure 2. Production Transformation Frontier for Returns to Agricultural Production vs Leasable Water

We find that, among water-limited options, the efficient set consists of seven activities: corn grain fully irrigated, silage fully irrigated, corn grain under limited irrigation, silage under rotational fallow, three-cut alfalfa fully irrigated, and two-cut alfalfa under rotational fallow, and lease all HCU activity. The CE for rotational fallow corn grain is nearly the same, a difference of little more than a dollar, as that for the limited irrigation strategy, and so are difficult to distinguish in the PTF. It is possible that more than one activity remains in the efficient set after applying this criteria. This is because no monetary value has yet been applied to the leasable water output and no definitive ranking can be determined in terms of a single metric. Notably, the efficient set here includes more ‘rotational fallow’ irrigation strategies than limited irrigation strategies. In addition, comparing certainty equivalents the rotational fallow strategy tends to have a higher CE than the limited irrigated strategy, practically independent of the choice of joint crop and harvest strategies with the exception of corn grain. This suggests that other strategies which might appear desirable because they keep more land in production would typically require higher payments for leasable water so as to remain incentive compatible with producers. We explore this idea further in the next section via breakeven analysis.

A comparative breakeven analysis, Table 7, finds the price the producer needs to be compensated to be indifferent between two cropping activities net transaction costs. Transactions costs could still be substantial and can have a large influence on whether a lease agreement will occur. All activities are compared to fully irrigated corn grain. The comparative breakeven shows the value for an acre-inch of HCU saved by implementing an alternative cropping activity and the value per acre-foot. The producer does not have an acre-foot available to lease from one acre if he implements one of the twelve selected activities. To achieve that much water, he would have to implement the cropping activity on multiple acres. The corn grain, limited irrigation activity has the lowest breakeven price. Based on the analysis this is the activity the producer would want to implement if he were to lease the water. However, he would only be interested if he was compensated more than the breakeven price, $381.95 acre/foot.

Table 7. Comparative Breakeven Analysis between Fully Irrigated Corn and Alternative Cropping Strategies a/

Crop Activity b/	Leasable Water acre-inches CU c/	Breakeven Price $/acre-inch CU d/	Breakeven Price $/acre-foot CU
C2	3.24	31.83	381.95
C3	3.24	32.17	386.05
S1	1.00	100.97	1211.61
S2	3.99	49.14	589.64
S3	3.99	44.51	534.11
A1	0.00	-	-
A2	3.24	70.85	850.19
A3	3.24	65.96	791.52
T1	5.21	56.24	674.83
T2	7.14	50.35	604.25
T3	7.14	45.24	542.94

a/ Fully irrigated corn is the reference strategy
b/ See Table 1 for a more complete description of the irrigated cropping activities
c/ Leasable water is the amount of the HCU that was not used for agricultural production
d/ Breakeven price is the amount to make the producer indifferent between a strategy. Fully irrigated alfalfa has no leasable water and breakeven price for water is not applicable

Figure 3 shows a comparison of all breakeven prices for ten of the cropping activities, which is used to combine agricultural profits, risk, and revenue from water transfers into a single comparative metric. Fully irrigated alfalfa did not reduce the consumptive use and so the comparative breakeven to find the price for the transferable water is not applicable. The first four activities with the lowest break-even price consist of the limited irrigated corn grain activity with the rest being rotational fallow strategies. The two activities with the lowest breakeven were the irrigation strategies related to corn grain, but the price for the silage crop activity is roughly 60% larger than that of the corn grain. The breakeven price for the silage, three-cut alfalfa, and two-cut alfalfa are similar values. The two-cut alfalfa, fallow activity had a low CE but frees up a considerable number of acre-inches for a potential lease, and so its breakeven price is comparable to other activities with much higher CE estimates. The silage, fully irrigated activity has the highest breakeven price. This is caused by a considerable reduction in gross margins while little water is reduced and available for temporary transfer. Limited irrigation strategies having a higher breakeven value, implies the opportunity cost of keeping more land in production through limited irrigation, rather than consumptively use the same amount of HCU with rotational fallow, is not cost effective with the exception of corn grain.

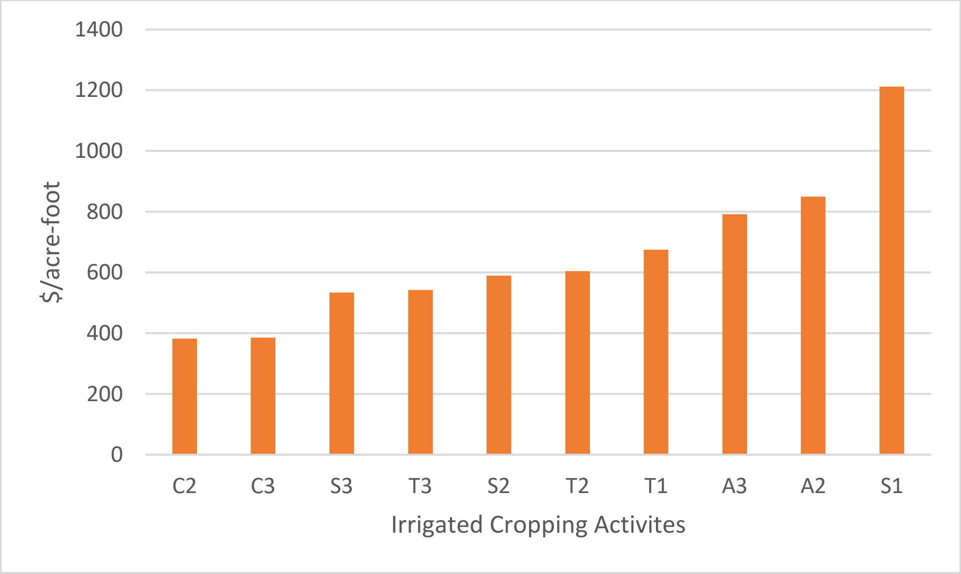

Figure 3. Breakeven Price for Cropping Activities with Leasable Water using Certainty Equivalents

When breakeven prices are calculated with means, Figure 4, the breakeven price is roughly 10 percent lower for limited irrigated corn, the activity with the lowest BEP. This could provide some insight on why producers may not be enrolling in ATMs. Producers are accounting for risk and the amount the amount that they would need to be compensated may be higher than previously thought. Also, the breakeven using means shows a greater difference between the rotational fallow and limited irrigated corn grain. When the activities are compared with CE, the activities have nearly the same BEP. Another difference between Figure 3 and Figure 4 is that the rank of cropping activities based on BEP changes. Specifically, limited irrigated silage and rotational fallow, two cut alfalfa with the former being ranked higher than the latter using mean switch places when using CE. Limited irrigation tends to look better when using mean values and not adjusting for risk. Rotational fallow strategies benefit from CE rankings because of their reduced risk profile.

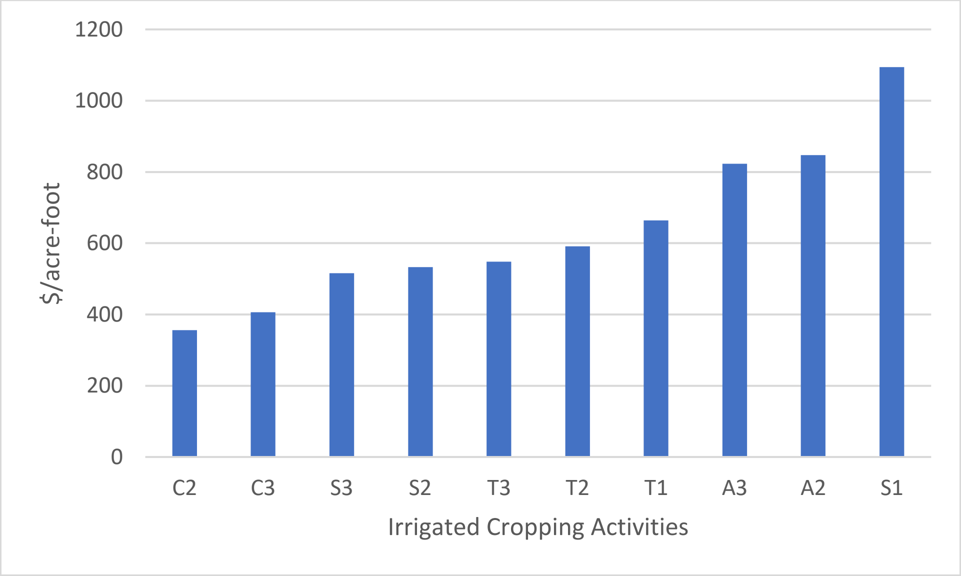

Figure 4. Breakeven Price for Cropping Activities with Leasable Water using Mean

5.4 Limitations

Some aspects of the framework and empirical case study limit the results in several ways. There are shortcomings of the model that could result in overestimating yields, which subsequently overestimates the gross margins and the minimum willingness to accept. The results are potentially limited by the crop simulation. It considers a single pricing scenario where decisions are made in the spring with water leased from agricultural to non-agricultural uses. For example, water lease prices might fluctuate throughout the season with some management options available to supply water to those markets at different times of the year. Producers' expectations about those prices and possibilities may also influence temporary leasing of water and should be considered. Also, it does not consider the attractiveness of purchase and lease back of water rights and other related options. Therefore, the case study is most appropriate for producers' whose long-term strategic planning includes continuing to farm.

The model assumes the land is productive, with maximum yields borrowed from a regional field trial. If the fields trial's yields are higher than an obtainable yield for the producer, the estimated yields for every cropping strategy are overestimated. This is important to consider because a farm that achieves lower yields has lower gross margins all else constant. With lower gross margins, the water has a lower opportunity cost and so value for the minimum willingness to accept is lower. Other crops, or activities like livestock production, that a producer might consider (e.g., wheat) were not included in the above analysis but this could be done in future studies.

Time is a critical component to irrigation and crop production. The precipitation data I use is measured seasonally over an assumed growing period for the crop. Timing of the precipitation is not captured in the model, which can change the potential yields. If most of the seasonal precipitation occurs in a short span, there is runoff or potential damages to the crop. Not having this distinguishability in timing could result in inaccurate estimate of yields and an unrealistic yield distribution. There are more advanced crop models, like the FAO AquaCrop, that could help address the concerns with predicted yields.

Crop quality influencing the price obtained is not captured in the model and the price of alfalfa varies on quality. Stressing the plant with limited irrigation could reduce the quality of the alfalfa. The alfalfa would not be able to be sold at premium prices. Alfalfa that is sold earlier may be a higher quality than the alfalfa sold later because of nutritional value. However, the yields for alfalfa from each simulation are treated as a homogenous product in the model. Crop insurance is not addressed in the analysis. Insurance would limit the downside of certain cropping activities, impacting the risk premium which could change producer's decisions. There are some products for limited irrigation that have recently become available but anecdotal evidence based on other research at Colorado State University indicates adoption is low.

Alfalfa and silage are not as easily transportable as corn. There may be a smaller market for these products, and this could make prices more volatile compared to a market with many buyers and sellers and this is not captured in the model.

The simplicity of the model is a potential strength. The production function does not have high data requirements and changing the assumptions for maximum yield could be adjusted for alternative soil types. The ability to use a crop coefficient model to predict yields and generate gross margins could be a low-cost tool for whole farm planning. Linear programming models can help with whole farm planning and there are models that do incorporate risk. A minimum of the absolute deviation (MOTAD) model could be used with the gross margins to determine potential optimal level of activity for each decision variable, acres planted under a specific cropping activity.

5.5 Implications for Producers and Leasing Water

Values obtained in the case study are not meant to be a decision tool for producers but are rather used to illustrate how the framework might be implemented and how results may be interpreted. The value from the case study breakeven analysis are large and based on the assumptions of the simulation, this producer may not be a viable option for leasing water based in the twelve selected activities. Northern Water's preliminary weighted average for awarded bids was $177.36 per acre-foot for a regional pool that opened May 16, 2019 (northernwater.org). There were only two accepted bids with prices above 200 dollars.

For alfalfa, corn silage, and two cut alfalfa, the fallow strategy has the lowest cost for an acre-foot of water. BEP for corn grain activities with leasable water are nearly the same. Limited irrigation is difficult to enforce, which makes it difficult to implement as a pseudo property right. Fallowing is enforceable. The crop type can be examined and through aerial imaging it can be determined if the reduction in acreage is adequate. If a partial fallow strategy and the amount earned from leased water is more profitable, then a producer with non-satiated preferences should choose fallowing over the limited irrigation strategies. There may not be a need to focus on developing laws to implement limited irrigation as a potential option when participating in an ATM from the producer's perspective. Based on the simulation results, producers are not going to choose that cropping activity if they cannot reach the full irrigation requirements for a majority of the crop and harvest strategies. In addition, limited irrigation for corn grain does not have a substantially larger gross margin than rotational fallow, and it may be easier to persuade the producer to adopt rotational fallow than trying to monitor the limited irrigation strategy.

CHAPTER 6 – CONCLUSION

In Colorado, alternative transfer methods are a possibility to reduce the permanent transfer of water from agriculture to municipalities and industry. ATMs create an incentive for producers to reduce their consumptive use because the water has an opportunity cost, the water can be leased. However, irrigation allows producers to mitigate variability in precipitation. Reducing the amount of irrigation water can expose the producer to more risk. This analysis explores the role of risk and its cost across twelve selected cropping activities a farmer might consider when participating in an ATM: two crops (corn and alfalfa), two alternative growing strategies (corn for silage and limiting irrigation to the first two cuts of alfalfa), and three irrigation strategies (fully irrigated, limited irrigated, and rotational fallow).

A model was constructed to estimate the distribution of gross margins for a producer in the South Platte Basin on well-drained silt loam soils. Yields were simulated using the FAO crop production functions, showing how these cropping activities might have performed from 1992 to 2017. A stochastic simulation analysis is used to compare the profitability of each cropping activity. Characteristics of the cropping activities influenced the mean, variance, and skewness of the gross margins. Following the framework of Chavas et al. (2009), we estimated risk premiums and certainty equivalents to evaluate the different cropping activities. Evaluating the cropping activities with certainty equivalents changed the order of desirability. A product transformation curve illustrating expected agricultural profits versus leasable water highlighted tradeoffs that producers face when deciding what irrigated cropping strategies to use with CU remaining on the farm. Using a comparative breakeven analysis (Dillon, 1993), we solve for a price for the leasable water available after adopting a cropping activity.

The strategies that involved rotational fallowing had higher certainty equivalents than the strategies that used deficit irrigation in the analysis with one exception corn grown for grain. Reducing the acreage is the more favorable strategy for a producer who is not going to fully irrigate the crop in most cases. It is difficult to administer a limited irrigation strategy for participation in an ATM. Trying to develop the legal framework to allow for a limited irrigation strategy may not be necessary because reducing the acreage generates higher agricultural returns and in the case of corn grown for grain nearly the same returns. A rotational fallow strategy is enforceable and typically has a lower breakeven price for leasable water.

There are limitations to the model. The crop production function does not differentiate between timing of precipitation and irrigation water. A potential robustness check for this analysis is using an alternative crop model that incorporates more data and considers the timing of irrigation and precipitation. Incorporating a more advanced crop model to capture time would provide a more accurate distribution of yields. In addition, the model does not differentiate between crop quality. Alfalfa's price can vary depending on the quality of feed, but in the analysis a single price is used. Using another program besides @Risk would make it more easily to perform robustness checks on the analysis.

Additional research related to alternative transfers and the viability of temporary transfers is necessary. Developing models that will help provide information and assist decision makers can help increase willingness to participate in ATMs. The information from the analysis is potentially helpful to both parties interested in participating in an alternative transfer; knowing where the other party stands is beneficial in negotiations. Future research could include following a similar procedure to this analysis but including a crop model that incorporates timing. It could also be beneficial to identify areas of origin where water alternative transfers are feasible and finding the economic impact an ATM would have on the area. Future research could look more at the added benefit of subsurface irrigation and its ability to reduce variability in yields.

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APPENDICES

Table A1. COAGMET Station and Years with Complete Seasonal Precipitation Data

		STATION ID													
		ftc01	ftc03	ksy01	alt01	ftl01	hxt01	lcn01	pkh01	ilf01	stg01	gly04	brg01	lsl01	ksy02
YEAR	1992	Y	X	X	X	X	X	X	X	X	X	X	X	X	X
	1993	X	Y	Y	X	X	X	X	X	X	X	X	X	X	X
	1994	X	Y	Y	Y	Y	X	X	X	X	X	X	X	X	X
	1995	X	Y	Y	X	Y	X	X	X	X	X	X	X	X	X
	1996	Y	Y	Y	Y	Y	X	X	X	X	X	X	X	X	X
	1997	X	Y	Y	X	Y	X	X	X	X	X	X	X	X	X
	1998	Y	Y	Y	Y	Y	Y	Y	X	X	X	X	X	X	X
	1999	Y	Y	Y	Y	Y	Y	Y	X	X	X	X	X	X	X
	2000	Y	Y	Y	Y	Y	Y	Y	Y	X	X	X	X	X	X
	2001	Y	Y	Y	Y	Y	Y	Y	Y	X	X	X	X	X	X
	2002	Y	Y	Y	Y	Y	X	Y	Y	X	X	X	X	X	X
	2003	X	X	Y	Y	Y	Y	Y	X	X	X	X	X	X	X
	2004	X	Y	Y	Y	Y	Y	Y	Y	X	X	X	X	X	X
	2005	X	X	Y	Y	X	X	Y	Y	X	X	X	X	X	X
	2006	Y	Y	Y	Y	Y	X	Y	Y	X	X	X	X	X	X
	2007	Y	Y	Y	Y	Y	X	Y	Y	X	X	X	X	X	X
	2008	Y	X	Y	Y	Y	Y	Y	Y	Y	X	X	X	X	X
	2009	Y	X	Y	Y	X	Y	Y	X	X	Y	X	X	X	X
	2010	Y	X	Y	Y	Y	Y	Y	Y	Y	X	Y	X	X	X
	2011	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	X	X	X
	2012	Y	Y	Y	Y	Y	Y	X	Y	Y	Y	Y	Y	X	X
	2013	Y	Y	X	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	X
	2014	Y	Y	Y	X	X	Y	Y	Y	Y	Y	Y	X	Y	X
	2015	Y	Y	Y	Y	Y	X	Y	Y	Y	Y	Y	Y	Y	Y
	2016	Y	Y	Y	X	Y	X	Y	Y	Y	Y	Y	Y	Y	Y
	2017	Y	X	Y	Y	X	Y	Y	Y	X	X	Y	X	Y	Y

Data are from https://coagmet.colostate.edu/

Table A2. CoAgMet Station ID and corresponding Station Names

Station Code	Station Name
ftc01	Fort Collins AERC
ftc03	ARDEC
ksy01	Kersey 1
alt01	Ault
ftl01	Fort Lupton
hxt01	Haxtun
lcn01	Lucerne
pkh01	Peckham
ilf01	Iliff
stg01	Sterling
gly04	Greeley 4
brg01	Briggsdale
lsl01	La Salle
ksy02	Kersey 2

Table A3. Price and Cost Data used in Simulating Gross Margins, Nominal Dollar Values

Year	Corn Price ($/bu) a/	Silage Price ($/ton) b/	Alfalfa Price ($/ton) a/	Corn VC ($/acre) c/	Silage VC ($/acre) d/	Alfalfa VC ($/acre)d/
1992	2.23	19.10	64.50	214.13	227.26	157.60
1993	2.65	19.90	77.00	221.73	229.45	154.11
1994	2.38	22.00	91.00	238.13	246.50	290.86
1995	3.33	22.00	88.50	241.45	255.27	255.31
1996	2.76	24.00	99.00	185.11	255.27	255.31
1997	2.59	24.00	101.00	185.84	262.17	296.67
1998	1.96	22.00	91.00	178.20	262.17	247.55
1999	1.84	20.00	69.00	175.74	262.17	281.84
2000	2.08	20.50	86.00	187.96	262.17	296.76
2001	2.13	22.00	101.00	194.71	262.17	296.76
2002	2.53	23.00	114.00	175.23	262.17	296.76
2003	2.49	22.00	85.50	195.01	279.24	211.08
2004	2.23	22.00	85.00	209.49	279.24	211.08
2005	2.23	21.00	101.00	215.52	279.24	366.00
2006	3.02	24.00	132.00	236.30	279.24	393.99
2007	3.96	32.00	139.00	246.44	551.47	494.13
2008	4.14	36.00	164.00	310.54	551.47	638.72
2009	3.68	28.00	136.00	292.27	551.47	562.72
2010	4.98	38.10	128.00	269.15	551.47	480.13
2011	6.15	47.05	209.00	309.06	560.31	501.82
2012	6.86	52.48	239.00	323.08	560.31	540.50
2013	4.61	35.27	237.00	329.61	560.31	482.69
2014	3.95	30.22	207.00	332.00	560.31	494.45
2015	3.69	28.23	179.00	304.25	560.31	498.66
2016	3.42	26.16	151.00	330.47	560.31	477.32
2017	3.35	25.63	168.00	323.46	560.31	458.87

a/ Corn and Alfalfa Prices are from USDA NASS

b/ Silage Price is from USDA NASS until 2010 after which this price is no longer tracked. Prices from 2010 onward are calculated as 7.65 times the price for a bushel of corn for the same year

c/ Corn variable cost is from USDA ERS for the prairie gateway region from 1996 to 2017. Variables costs pre-1996 are from CSU Crop Enterprise Budgets

d/ Silage and Alfalfa variable costs are from CSU Crop Enterprise Budgets. If data was not available from a year, it was assumed to be the same as the closest previous year with available data.