THESIS

CORN GROWER CHANGE FOR CLIMATE CHANGE: EX-ANTE ECONOMIC ANALYSIS OF ADOPTION OF ENHANCED ROOT TRAITS

Submitted by

Angelique Giraud

Department of Agricultural and Resource Economics

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Master's Committee:

Advisor: Gregory Graff

Daniel Mooney
John McKay

ABSTRACT

CORN GROWER CHANGE FOR CLIMATE CHANGE: EX-ANTE ECONOMIC ANALYSIS OF ADOPTION OF ENHANCED ROOT TRAITS

Sustainable agriculture technologies of enhanced root corn possess the potential to offset more than half of the greenhouse gas emissions of the transportation sector if completely diffused. Weather variability resulting from climate change is predicted to decrease agricultural productivity. Enhanced corn root traits aim to mitigate and adapt to climate change by improving drought tolerance and soil quality and increasing carbon sequestration rates. Encouraging adoption is challenging among heterogeneous corn growers in an enormous market. Previous research on farmer preferences around four categories of benefits stemming from adoption of corn with enhanced root traits frames the motivation to detail profit margins influencing business decisions utilizing a linear programming model. Several scenarios of changes to cost, revenue, carbon sequestration, and water scarcity are analyzed to provide guidance for policy. Results indicate that a corn grower will not choose enhanced root corn when the only benefit is carbon sequestration with cost and revenue as sole drivers of the decision to adopt. As water scarcity progresses, drought tolerance becomes increasingly valuable, substantially shifting production decisions in favor of adoption of corn with enhanced root traits.

ACKNOWLEDGMENTS

I would like to acknowledge my advisor, Dr. Graff, for guiding me in developing this thesis and understanding the larger ROOTS project. This work would not be complete without the help of my committee members Dr. Mooney and Dr. McKay. Research conducted through the ROOTS project, led by Dr. McKay inspired this economic analysis. All of the professors of the DARE program contributed to my economic knowledge building a solid foundation for me to write my thesis. Thank you all.

DEDICATION

This work is dedicated to my father, Jean-luc Giraud. He first instilled in me a passion to learn about and improve the world around me. The work ethic he taught me is the only reason I could complete this difficult task. Forever, he forces me to ask questions and find the answer myself. Jean-luc inspired me to come back to school to pursue a quantitative master’s degree. He always worked to make the world a better place. Now after his passing, there is a greater gap in the world that this research seeks to help fill.

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CHAPTER 1 INTRODUCTION

An incipient opportunity to mitigate climate change through large-scale carbon sequestration lies buried in US agricultural soils. Full scale adoption of corn with enhanced root traits has the potential to offset more than 50% of emissions generated from the nation's transportation sector. This paper addresses the question of how to influence rapid and complete adoption of corn with enhanced root traits.

Altering land use management is the most cost-effective action to mitigate climate change and inaction risks losing the economic security bestowed by our working lands. Corn is the most widely grown crop in the country. Research through the US Department of Energy is working to identify genetics of corn that enhance root traits to increase carbon sequestration, improve soil quality, and boost drought tolerance serving to both mitigate and adapt to climate change. Full impact to sequester carbon and offset greenhouse gas emissions requires adoption by 100% of US corn growers.

Corn producers have widely varying operations and preferences. There is no single mechanism that captures incentives for every farmer. The most challenging group to persuade to adopt new sustainable technology are those that face tight revenue and cost margins and those with limited options for buying seed and selling grain. A linear programming model is used to identify the margin of profits that shift decisions under varying incremental scenarios of carbon sequestration, drought tolerance, and water scarcity.

Globally displaced populations, greater climate variability, and innumerable other life-threatening challenges are the predicted effects of climate change. One of the greatest obstacles to overcome in the next few decades is the increased strain on agricultural production caused by greater potential for drought and altered weather patterns. Exacerbating the problem, current production rates will be outpaced by the demand for food by the year 2050 (Tilman et al., 2011, Odegard and Van Der Voet, 2014). It is expected that we will need to produce 60% more food by 2050 than at the beginning of the century (Xu, Twine, & Girvetz, 2016).

The most recent report by the Intergovernmental Panel on Climate Change lays out limited paths to address climate change due to sluggish action and even movement in the opposite direction. International agreements cite the goal of limiting the most disastrous effects of climate change through emissions reductions and active sequestration of greenhouse gases (GHG). The most realistic and cost-effective way to do that will be to adjust management of our working lands.

Land use management is a major source and sink for GHG. Soils are the greatest terrestrial organic carbon sink, capable of storing three times the current amount of carbon dioxide in the atmosphere and 240 times the annual emissions from fossil fuels (Paustian et al., 2016). Methods developed through the green revolution and beyond have allowed agricultural production to increase tremendously (Pingali, 2012), but with large social costs to the environment through soil depletion, erosion, overconsumption of water, water pollution, and release of GHG. About 40% of the worlds land is devoted to agriculture (Wossink & Swinton, 2007). Agricultural production is directly responsible for 9-14% of GHG emissions from soils and livestock (Paustian et al., 2016). Research through the US Department of Energy seeks to make field cropland a net carbon sink (ROOTS, 2016).

Compounding the barrier of producing enough food to meet the demands of a growing population, climate change decreases the ability to produce at the current rate using the current technology. Schlenker, Hanemann, and Fisher (2006) find that a majority of cropland will suffer losses from global warming. The article determines that temperature and precipitation changes alter productivity and result in a 10-25% decline in the value of agricultural land east of the 100th meridian by 2050.

Additionally, research specifically modeling corn production in Iowa forecasts a decline in yield by 2050 without adaptation to or mitigation of climate change (Xu, Twine, & Girvetz, 2016). Models comparing increased temperatures with and without moisture stress reveal the importance of irrigation and drought tolerance. For Iowa, an increase of 1°C there is a 6% reduction in maize yield. When the effect of moisture stress was removed from the simulation, the yield decrease fell to 3%. The authors note that through increased use of irrigation, yield losses could be decreased. Notably, even when water is not a limiting factor, by the end of the century yields are predicted to decrease by 10-20%.

Departing from the Malthusian underestimation of the ability of humans to adapt agriculture to fit the needs of our growing population this research takes the view that we are not doomed to starve and fall into societal chaos. Yet, we cannot sit back and hope for the best. New agricultural technologies are constantly being developed; the question is how to transition.

A component of increasing return on investment in developing sustainable agricultural technologies is to ensure they are employed thoroughly and swiftly throughout the sector. Contributions of this paper include a comprehensive synthesis of research on farmer preferences and details of unique and valuable information about the margin of profit that will shift the decision of the farmer to adopt conservation technology. Many other technologies have hit impediments limiting adoption. Learning from previous pitfalls, this paper outlines a path to implement policy to promote widespread diffusion on enhanced root structure corn.

This thesis reviews some challenges to mitigation and provides motivation to overcome those challenges. In the Economic Theory section, research on farmer preferences is dissected in context of four categories of benefits provided by enhanced root corn. Methodology and Data describe the linear programming model and how it is used. The Results and Discussion section lay out producer decisions under various scenarios. Finally, the Conclusion summarizes and provides implications for policy.

CHAPTER 2 MOTIVATION TO OVERCOME CHALLENGES TO MITIGATION

2.1 Negative Externalities

Climate change is a consequence of market failures in accounting for the external costs of production activities. For example, electric generation from fossil fuels provides electricity at a low cost to consumers. The price of electricity is historically determined through cost of capital, labor, and fossil fuel inputs. External costs of carbon pollution, previously ignored, are already being felt and are likely to increase substantially. Damage to coastal cities caused by sea-level rise and increased prevalence of drought and wildfires are among the list of likely outcomes. The costs of climate-related destruction are shirked by producers and borne by the global public now and for generations to come. This same market failure is present in most production practices.

Modern agriculture provides an abundance of food at low cost to consumers. Agricultural markets are responsible for several negative externalities. Agroecosystems are made of myriad connected functions and depending on management can provide private and public positive services or loss of capacity.

Although best management practices are available, they are not adopted widely enough to prevent external costs of production with negative social welfare impacts. Production methods on the market aimed at improving soil quality and reducing greenhouse gas emissions have had limited uptake. For example, cover crops and reduced and no-tillage techniques decrease emissions substantially (Camargo et al., 2013), increase profits and have positive impact on social welfare (Archer et al., 2008), but are not as widely adopted as necessary for large scale emission reductions needed to meet goals (Wade et al. 2015).

Adoption of corn seed with enhanced root traits has the potential to improve social welfare by decreasing negative externalities and incorporating positive externalities bringing the supply of corn closer to accounting for the social cost of production. The range of ecosystem services impacted by the associated agricultural externalities are examined further in later sections.

Figure 1 shows an example of how supply would shift after accounting for the externalities of production with conventional seeds and seeds with enhanced root traits. Externalities are unique to each crop. For conventional corn, production externalities may include soil erosion, nutrient pollution, wasteful water use, and greenhouse gas emissions.

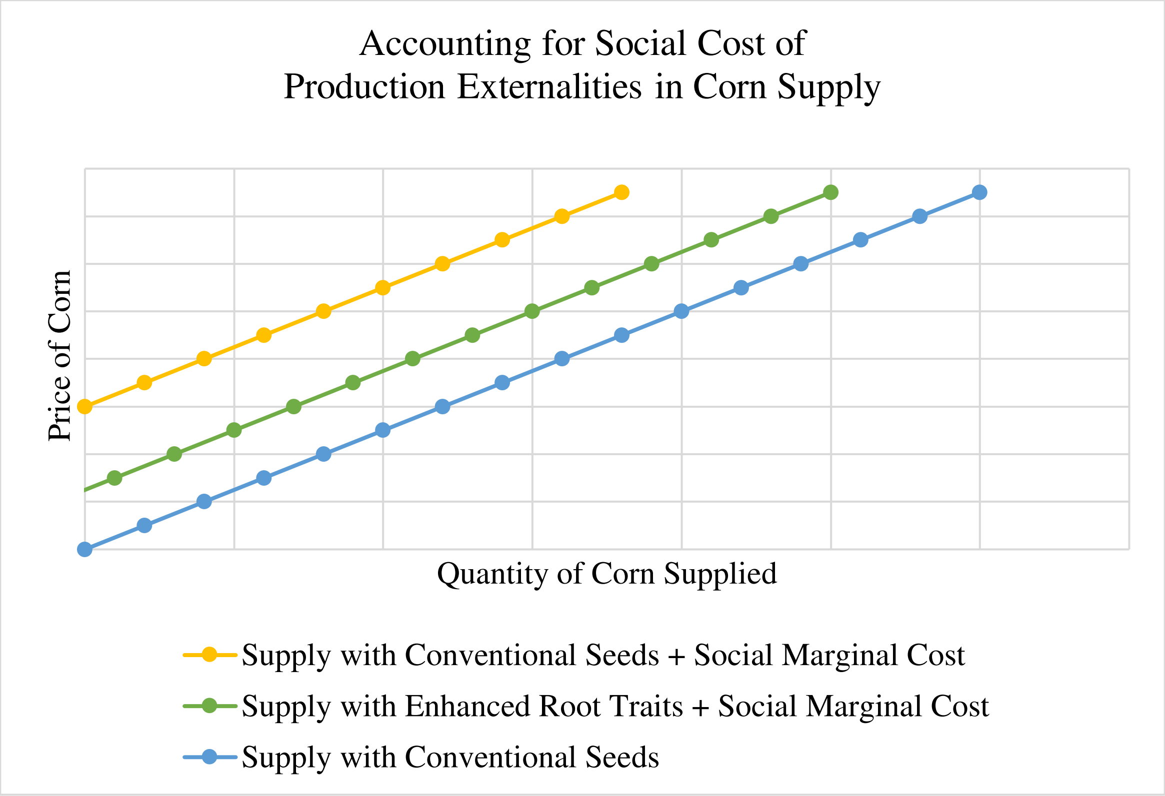

Figure 1. *A comparison of corn supply accounting for social cost of externalities from conventional seeds to seeds with enhanced root traits.*

2.2 Competition between Land Use for Food and Forests

Lubowski, Plantinga, and Stavins (2006) estimated the carbon sequestration supply function for forest-based carbon sequestration. They identify opportunity costs of transitioning six major land uses to forested land incentivized through carbon payments. Their research suggests that increasing forested land will be a cost-effective method of reaching the target levels of atmospheric carbon. Part of the results include the transformation of cropland to forest. The growing demand for food will make that transformation increasingly unlikely, even with their considerations of opportunity costs.

A special report from the Intergovernmental Panel on Climate Change discusses the potential for carbon sequestration through converting non-forested land to forested land, which would come at a cost to food security (Rogelj et al., 2018). Rather than write off crops as a net carbon emitter, the advances of genetics and breeding allow crop scientists to predict a more dynamic future. The ultimate goal of ROOTS (2016) research is to make cropland carbon sequestration a measurable reality.

2.3 ROOTS Research: Root Genetics for Drought and Carbon Adaptation

Current research of the US Department of Energy, Rhizosphere Observations Optimizing Terrestrial Sequestration, ROOTS, (2016) seeks to identify genetic traits of corn germplasm that fundamentally change the structure and function of corn roots. Three enhanced root traits are targeted, drought tolerance, soil quality improvement, and carbon sequestration. These traits act to both adapt to changing weather patterns caused by and mitigate against climate change.

Researchers estimate that corn with enhanced root traits has the potential to capture a substantial amount of carbon and store it in the soil, such that a 100% transition to ideal enhanced root corn varieties would offset more than 50% of the emissions from the entire US transportation industry. The map and graph below in figure 2 portray the biogeochemical possibility to store carbon in agricultural soils through development of these traits.

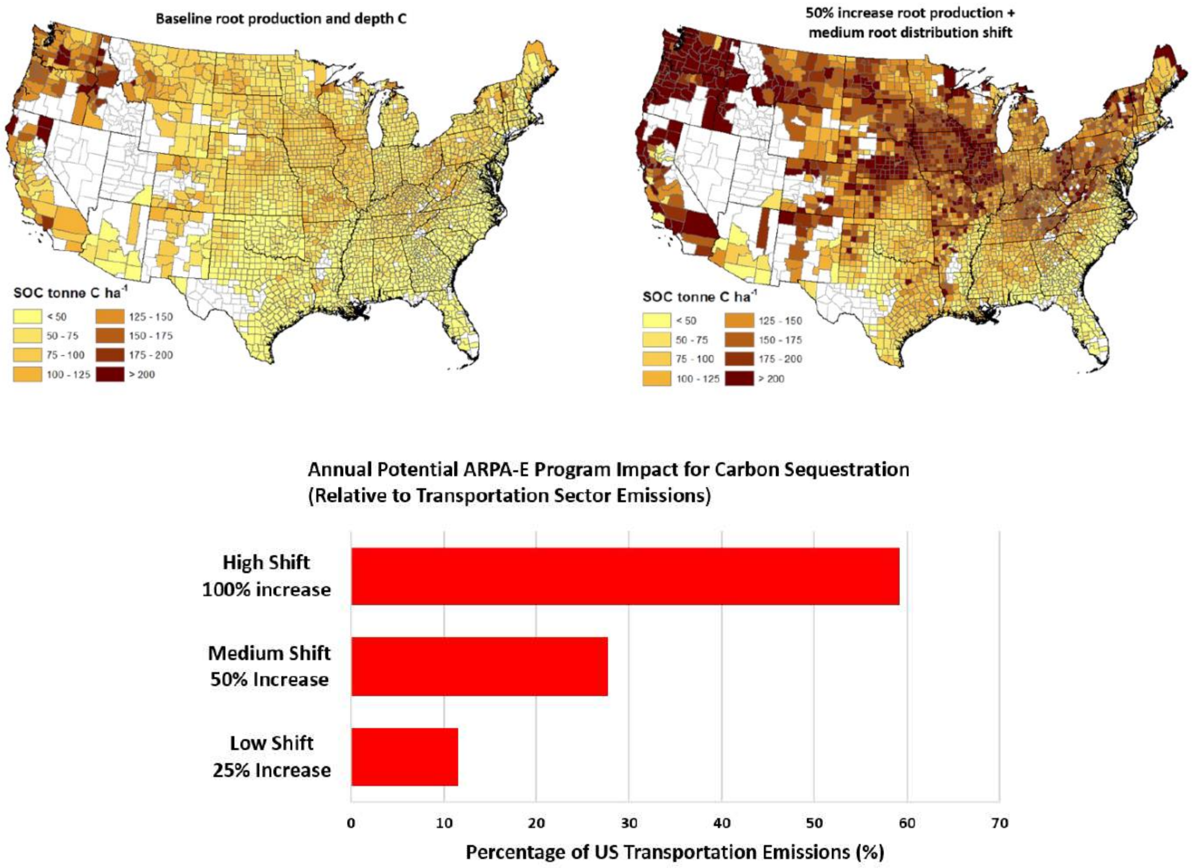

Figure 2. *Soil carbon sequestration potential*
Geographic distribution of steady-state soil organic carbon (SOC) stocks (0-200 cm) on cropland and pasture/hay land under baseline (i.e. current) conditions and under a scenario for 50% increased root carbon inputs and deeper root distributions. In the bar chart at the bottom, the sequestration potential of the modeled acres is the aggregation of simulations of increased root mass [+25,50,100%] and increased root depth [Low (20% of biomass shifted to next lowest root layer), Medium (annual crops shifted to grass/hay root profiles), High Shift (all crops shifted to a model root distribution)] at steady state.
Source: ROOTS, 2016.

2.3.1 Drought Tolerance

Changing weather patterns and increased occurrence and intensity of drought are forecasted effects of climate change. Drought reconstruction models developed for the Southwest and Central Plains regions ominously indicate unprecedented risk of severe drought after 2050

(Cook, Ault, & Smerdon, 2015). A similar predication is found for Rocky Mountain states (Strzepek, Yohe, Neumann, & Boehlert, 2010).

Suboptimal water use in agriculture encumbers the larger community dependent on that watershed and future communities. Improving water efficiency will save input costs for the farmer and can protect the public water supply from overconsumption.

Irrigation water is a direct cost to farmers, is likely to become more expensive, less available, and suboptimal use has external impacts. The Ogallala Aquifer supplies 30% of the irrigated groundwater in the nation and supports the area of highest agricultural market value in the US. Several scenarios of business-as-usual and decreased pumping rates give pictures of possible future water supply fates (Steward et al., 2013). An important finding is that reducing water use now and for decades to come will provide a sustainable source of water in the next 100 years as crop water use efficiencies are increased.

A study by the Economic Research Service of the USDA looked into adoption of drought tolerant varieties of corn in the US. A few drought tolerant varieties have been on the market since 2011. Moving from just 2% of planted acres in 2012, diffusion of drought tolerant varieties throughout the country reached 22% in 2016. States with higher drought risk and recent drought exposure saw diffusion rates up to 42% in Nebraska and 39% in Kansas. Figure 3 and 4 show maps of diffusion of drought tolerant corn and drought severity during the corn-growing season. The price premium for the drought tolerant trait was estimated at about $10 per bag of seed averaged over all states in the study (McFadden, Smith, Wechsler, & Wallander, 2019).

The trait of drought tolerance is expected to keep yield high or even increase yield under normal conditions and prevent yield loss in drought conditions. McFadden et al. (2019) also find that for irrigated fields with drought tolerant corn, yields were 11% higher, a statistically

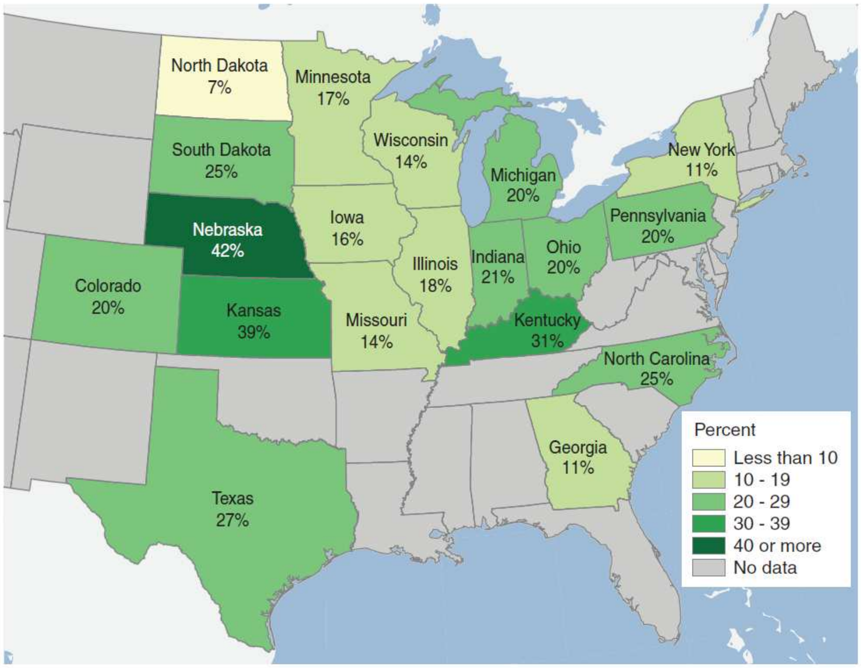

Figure 3. *Percent of each State's corn acreage planted with drought-tolerant hybrids, 2016.*
Source: USDA, Economic Research Service and National Agricultural Statistics Service, 2016 Agricultural Resource Management, as cited by McFadden, Smith, Wechsler, & Wallander (2019)

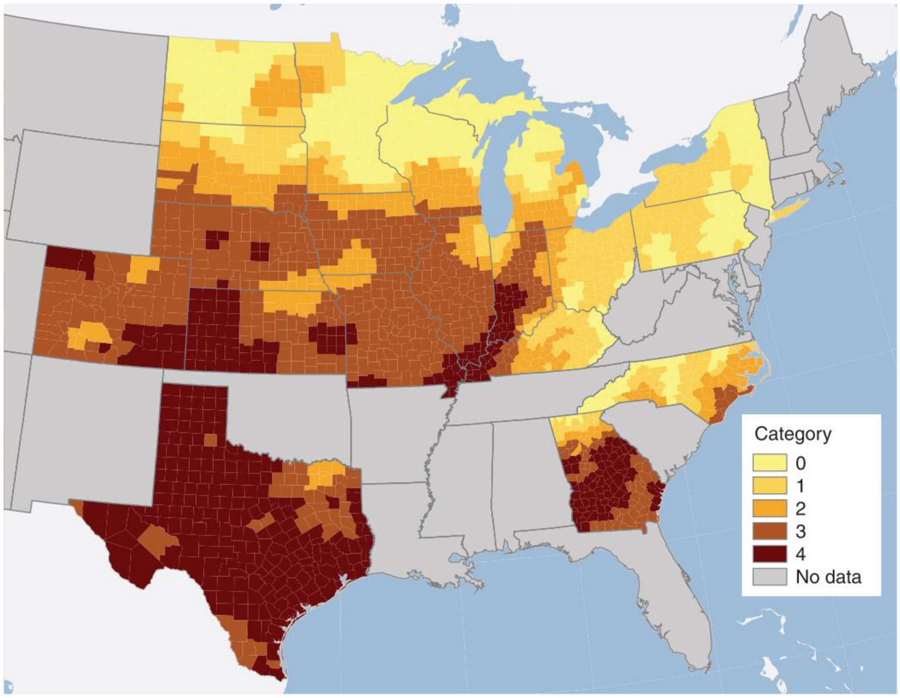

Figure 4. *Most severe drought during corn-growing season 2011 - 2015, by county*
Source: National Drought Mitigation Center at the University of Nebraska-Lincoln, USDA, multiple agencies, and the National Oceanic and Atmospheric Administration, 2011-15 U.S. Drought Monitor, as cited by McFadden, Smith, Wechsler, & Wallander (2019)

significant gain. Though statistically insignificant for dryland, yields were 4% higher. They do offer the caveat that a producer that adopts drought tolerant corn may also implement other water conservation practices and utilize greater inputs (McFadden, Smith, Wechsler, & Wallander, 2019).

Use of drought tolerant crops that require less water may allow the farmer to grow more crops, leaving overall water use constant. This is still a more efficient use of water, decreasing the marginal external cost of growing a bushel of corn. Alternatively, crops requiring less water may provide alternative income by selling water to another firm such as with deficit irrigation.

2.3.2 Soil Quality

Enhanced corn root structure aims to increase underground biomass and build up soil organic carbon, making soils healthier and preventing erosion. Improvement of soil quality will have private benefits as well as external benefits, such that growers may not need incentives to adopt. Soil quality has important private pecuniary implications of input use, yield, and farm longevity as well as to public goods. Soil quality regulates water holding capacity, water quality from resulting erosion of soil and runoff of fertilizer and pesticides, PH buffering, biogeochemical cycling, and are regionally specific (Kremen et al., 2012). Soil quality degradation began decades ago in many areas, and benefits are expected to accrue over many years after adoption.

2.3.3 Carbon Sequestration

Growing corn releases greenhouse gases including carbon dioxide and nitrous oxide, which contribute to climate change. Greenhouse gas emissions contribute entirely external costs and carbon sequestration provides public benefit by mitigating damages of climate change. Motivating farmers to sequester carbon is expected to require pecuniary incentives.

CHAPTER 3 ECONOMIC THEORY: INCENTIVE CATEGORIES AND FARMER PREFERENCES

Aiming for 100% of corn farmers to change their production practices and adopt sustainable technology requires broad diverse incentives and attention to market dynamics. Adoption of new technology by farmers is heterogenous across groups and regions and depends on the qualities of the technology.

The US is the largest producer of corn in the world, producing 14.7 billion bushels of corn in 2017, with regional differences in production practices. The competitive landscape of corn farming is characterized by a large number of relatively small operators; 83.8% of farms plant on less than 500 acres growing 37.4% of total bushels produced. A comparatively small 5.8% of all operations are larger than 1,000 acres but grow 36.7% of total bushels of corn produced. In other words, over 250,000 small farms produce about the same quantity of bushels of corn as almost 18,000 large farms. Both of these populations represent a substantial portion of US corn production, yet both run very different operations. Figure 5 shows more about the operation size breakdown.

Incentives that work for one farm may have little influence on any other farmer. The barriers to adoption of conservation techniques are different among heterogeneous groups (Grand et al., 2017). There is no approach to agriculture technology adoption that works for every farm. Each new technique needs an individualized plan for widespread implementation. The diversity of this industry creates a barrier to any one-size-fits-all approach.

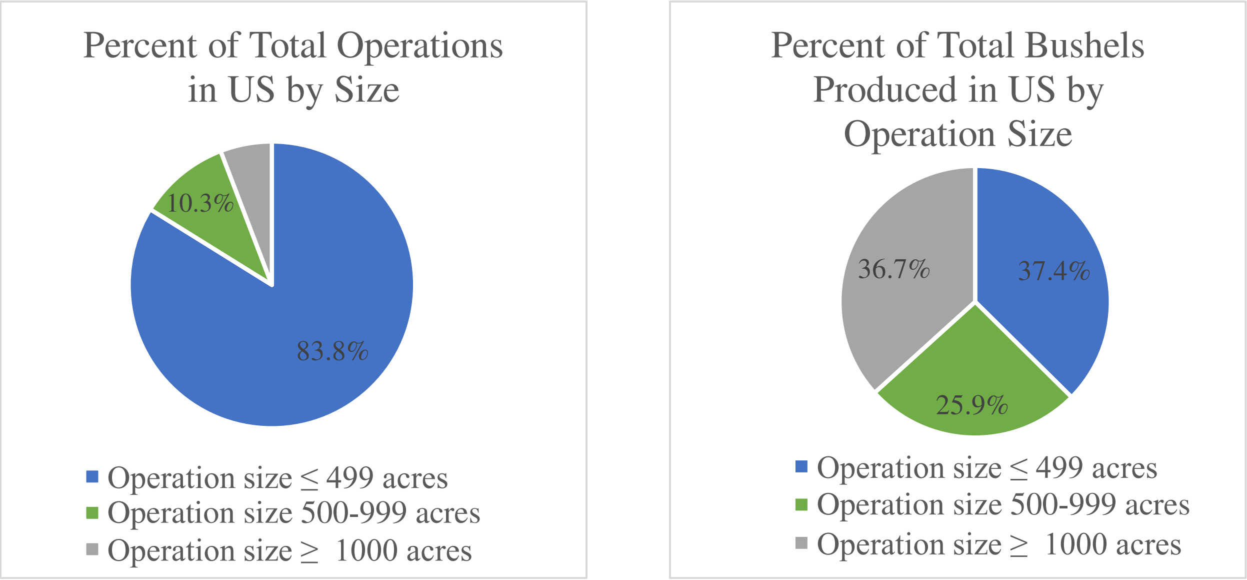

Figure 5. *Graphs of US corn for grain production organized by operation size*
Percent of total for number of operations and bushels produced.
Source: 2017 Census of Agriculture - UNITED STATES DATA USDA, National Agricultural Statistics Service

In addition to reviewing literature, several farmer interviews were conducted to guide research. The following incentive structures were discussed with corn farmers in Colorado and the review of literature on farmer preferences aligned with issues covered in these consultations. Interviews were structured with broad open-ended questions related to water use, risk, soil quality, adopting new technology, community and network, climate change and carbon sequestration, and incentive mechanisms for providing ecosystem services.

Incentive structures fall into four categories to capture all of the possible motivations of myriad corn growers. These broad categories explore the role of monetary and non-pecuniary utility-based incentives. Farmer preferences related to these incentives are reviewed.

3.1 Category 1: Short-term, private, pecuniary benefits to farmers

Category 1 encompasses short-term, annual, incentives with private monetary benefits. These include payment or cost reduction mechanisms. Three alternative routes to adjust Category 1 benefits are described.

One, in some markets a price premium will be available as industry aims to offset the carbon footprint resulting from their own production practices. This mechanism incentivizes seed choice through increased revenue. Not all markets will offer a higher price for corn.

The second route is through reduced seed costs. A company interested in offsetting their emissions can provide funds to seed suppliers such as Monsanto or Corteva to offset the cost of sustainable seeds to induce farmers to purchase these. Ideally this program would be developed with a level of transparency, where a third-party group like The Nature Conservancy provides accounting of the tons of carbon offset through purchase and planting of these seeds. This could be limited in certain areas that do not have the same range of seeds to select from.

The third mechanism to impact annual profits would be to offer a technology rebate for participating in conservation practices. One method to provide this is through the government, such as through a Farm Service Agency program. Similarly, a rebate could be offered through reduced insurance premiums. As drought tolerance traits reduce the need for insurance payouts, farmers should be rewarded for such actions through reduced costs.

Chouinard et al. (2008) find that farmers may fall into two broad groups: those whose primary motivations are about themselves, and others who are socially motivated. The latter group are found to forego some profits to adopt conservation practices. They suggest further that some incentive such as a subsidy would promote wider adoption of such agricultural techniques that do sacrifice profit for an environmental benefit.

Willingness to accept payment for carbon sequestration through three mechanisms were investigated (Gramig & Widmar, 2018). The least favorable mechanism is a carbon market ($12.78/acre), government payments are in the middle ($2.48/acre), and an increase in revenue through a decrease in input costs or increase in output value is the most favorable mechanism.

The enhanced root traits of this study are not expected to impact profit negatively, though there is uncertainty around how the market players will capture profits around these traits. Seed pricing becomes an important influence of diffusion, only a slight increase will deter adoption (Lybbert & Bell, 2010).

The US corn seed market has been highly concentrated among six large firms (Shi, Chavas, & Stiegert, 2010), which has been further reduced to four due to recent mergers. These authors examine seed pricing, finding regionally specific price discrimination, higher prices under imperfect competition, and mergers have the potential to increase conventional seed prices.

A trait-based model is used to understand farmer preferences for corn varieties' crop traits (price differential, yield advantage, and savings in herbicide, insecticide, and labor/management inputs, GM/non-GM) and farm and farmer characteristics (Useche, Barham, & Foltz, 2009). Yield increases result in higher willingness to pay, while a greater price differential has a significantly negative effect. Greater farm revenue also decreases price sensitivity. Higher savings for herbicide, pesticide, and labor increases the probability of use of the seed. Regional variability showed changes in magnitude, while overall results were of consistent direction. The authors end with suggestion that future research should cover the adoption rates for difference in yield for drought-tolerant crops.

The economic impact of soil conservation policies in the Corn Belt are examined with a linear programming model (Osteen & Seitz, 1978). The model predicts that economic incentives are needed to encourage adoption of conservation tillage methods to reduce soil loss, though not necessarily through government financial assistant. Instead the study recognizes the need for farmer education of financial benefits incurred by conservation tillage.

Chambers and Just (1989) use a crop-specific profit function to measure the marginal benefits of inputs in producing a single output and expand to develop a multi-crop profit function to compare allocation of inputs for different choices in outputs.

The impact of adoption of three categories of best management practices (BMP) on farm profitability are examined by Valentin, Bernardo, & Kastens (2004). Survey data from Kansas farms are used to evaluate the net farm income and adoption rates of nutrient, pesticide, and soil conservation BMPs for four types of crops including corn. The profit model is not designed to predict profit, instead the researchers aim to elicit the impact of BMP adoption on profit. Their methodology is reflected in this current work, as can be seen in this version of the model:

$$Net\ farm\ income = labor\ hours + \sum(crop\ acreage_i + BMP\ adoption\ indices_i)$$

Similarly, an economic optimization model is developed to improve decision making on crop selection and irrigation management, deficit irrigation (Li, Hu, Jubery, & Ganapathysubramanian, 2017). Their model provides decision support and risk analysis for farmers with limited and expensive water resources. One of the unintended outcomes of policies limiting carbon emissions are distributional impacts. Major emitters required to meet limits can be expected do so through the most cost-effective ways. Firms can change the technology or fuel used or purchase additional emissions permits from other firms in the carbon market. An increase in the cost of electricity is a probable outcome, adversely effecting consumers of electricity, including farmers. Offsetting such distributional impacts are important considerations in developing policy for incentivizing adoption of climate change mitigation technologies.

Konyar (2001) developed a mathematical programming model to estimate effects of higher energy prices on US crop production implemented under the Kyoto Protocol to reduce greenhouse gas emissions. A carbon charge of $348 per metric ton of carbon emissions, increases direct and indirect energy prices, forcing farmers to substitute out from energy-intensive inputs such as irrigation, fertilizer, and fuel to lower energy inputs of land, labor, and capital. Flexibility of substitution on US crop land allows for a 20% reduction of GHG emissions with a relatively small decrease in total harvested acres, and still an increase in profits. One of the major assumptions in this article is that farmer will substitute away from irrigated crops in favor of dryland cropping. Although lower yields are an expected outcome of this, the authors do not include a change in yield due to climate variability predicted in other studies such as Xu, Twine, & Girvetz (2016). This supports the need for drought tolerant varieties to help farmers adapt.

3.2 Category 2: Medium-term, risk based private benefits to farmer

Category 2 considers a medium-term of 3-7 years. This is the timeframe where reduced risk plays a role in decisions to adopt new technology. The use of corn that is adapted to changing climate and weather patterns helps to mitigate associated risks. Having a more reliable yield impacts expected profit and expected value. In some places risk is not as big of a concern as other areas. Here there are monetary and utility-based motivations.

Lapple et al. (2013) find that social acceptance of new technology limits adoption beyond economic and technical variability. A similar finding comes from a study on choice of tillage practice used for dryland corn (Canales, Bergtold, & Williams, 2018). The authors note that previously no-till was perceived as risk increasing. Over time, as the practice was more widely adopted with favorable results, they suggest that the common perception switched to view it as a risk-reducing activity. The decision to adopt conservation tillage seemed to be independent of the production system, suggesting the need for education of complementary practices.

Foltz, Useche, and Barham (2013) use an ex-ante trait based model to estimate heterogeneous farmer willingness to pay for technology traits and the mechanism of receiving benefits: purchase of a seed that guarantees 75% of area based yield (warranty), or a drought tolerant seed that will yield 75% of the yield in a severe drought year. The model used here looks at the willingness to pay (WTP) for a technology that reduces risk. The WTP for one trait is specified in terms of the farmers preference relative to their price sensitivity.

$$WTP_{x1} = \frac{dp}{dx_1}$$

$$WTP_{x1} = \left(\frac{\beta_1}{\alpha}\right) + \left(\frac{\beta_2}{\alpha}\right) * \left(\frac{dx_2}{dx_1}\right) + \cdots + \left(\frac{\beta_k}{\alpha}\right) * \left(\frac{dx_k}{dx_1}\right)$$

Where $WTP\ x_k$ is the farmers willingness to pay for a seed with k traits and β_k is the farmers preference for that trait, and $\frac{\beta_1}{\alpha}$ is the effect of risk reduction on utility, and the indirect effect of that trait interacting with other traits.

Farmers show higher WTP for drought tolerant traits built into the seed ($17-20) compared to seeds bundled with a warranty ($9-10). It is hypothesized that some of this difference is explained by farmers expecting that the drought tolerant trait will improve yield across the distribution. Farmers in more drought-prone areas are willing to pay more for the drought tolerant trait built into the seed. Farmers who buy crop insurance are willing to pay more for the warranty and the built-in drought tolerant trait. Trust in seed companies was also significant, farmers that trust seed companies are willing to pay $6.40-7.60 more for the bundled warranty, but that did not factor into their WTP for drought tolerant trait.

Research has also found potential for moral hazard. Having crop insurance was negatively associated with adoption of risk-reducing conservation tillage practices (Canales, Bergtold, & Williams, 2018). They argue that interaction of insurance and adoption of risk-reducing technology should be further considered by policy makers. In contrast McFadden et al. (2019) find that 84% of fields that adopted drought tolerant corn are covered by Federal crop insurance which is greater than 76% of non-drought tolerant fields, though the type of insurance was not significant.

3.3 Category 3: Long-term private benefits to farmer

Category 3 covers long-term private incentives. As soil quality increases over time, this in turn can push up property values and allow for fewer inputs. The asset valuation perspective is expected to be different for farmers that own their land compared to farmers that lease their land. This is likely to have utility as well as pecuniary impacts.

A complicating factor is the operator/owner status of farmland, with 39% of US farmland rented, and the majority owned by non-operating landowners (Ranjan et al., 2019). Barriers such as risk aversion and lease contract renewal hinder adoption of conservation practices. The authors suggest that government programs offer communication and lease tools to increase adoption.

Three natural resource conservation technologies (conservation tillage, soil nutrient testing, and integrated pest management) are analyzed over a long period (1940-1990), using an economic duration model to a national sample of US farms (Fuglie & Kascak, 2003). A logistic distribution function is used to estimate a diffusion path given by

$$S(t) = \frac{1}{1 + (\lambda t)^p}$$

where S(t) is the proportion of the population that has not yet adopted at time t and λ and p are estimated parameters. The marginal effect of adopting a specific practice measures the lag in adoption behind the expected adoption time of a representative farm given by

$$\frac{\partial t_m}{\partial X_k} = \beta_k \exp^{\beta' X_m}.$$

Where $\beta_k > 0$ indicates that X_k increases adoption lag and $\beta_k < 0$ indicates that X_k increases rapid adoption by a farm with K characteristics.

Various interesting and relevant findings result including, higher levels of education, larger farm size, and higher quality land were significantly associated with more rapid adoption of all three technologies by as much as one or two decades.

3.4 Category 4: Long-term benefits to public

Category 4 are the broad, long-term, public benefits. This is where a farmer may or may not consider environmental sustainability of their actions from a public or even global perspective. Converting to enhanced root corn is expected to have significant impact on the climate. Climate change is big picture problem. Many farmers to do not see the climate changing over the generations of their farm. The variability in weather they experience is normal to their lives. Even if they believe climate change is occurring, they may not believe their own private actions have any impact. This view and understanding of climate change may impede any action that is not monetized. This of course is not necessarily the view of all farmers. Those that are aware of climate change and environmental sustainability may not need private incentive to adopt, but the profit margins of the corn market are so narrow, they may not have the room to act as a business as they would ideally want to.

Production of ecosystem services from enhanced root trait varieties exhibits a dynamic joint relationship with corn farming. Drought tolerance, soil quality improvement, and initial annual carbon sequestration produce a complementary relationship with corn production. Addition of requirements to maintain carbon captured in soil long-term, changes to a competitive production relationship. Beyond the initial year the jointness relationship changes, the farmer loses the option to choose alternative seeds and practices and would thus need payment for the production of that service (Wossink & Swinton, 2007).

A particularly interesting finding from Fuglie and Kascak (2003) is that there is a 21-year difference between when the largest farm class and the smallest farm class adopt soil nutrient testing. In reference to carbon sequestration, requiring farms to test their soil for a carbon benchmark is expected to create a similar lag. It could be recommended that a large farm conduct soil carbon testing and share results with neighboring smaller farms, or the government or companies interested in carbon offsets could fund testing in a region to develop soil carbon storage benchmark and potential. While the mechanism for soil testing is uncertain, every effort to reduce the burden of soil carbon testing on small farms will increase the likelihood of adoption.

Robertson et al. (2014) also discuss that large farms are more willing to adopt more complex conservation techniques compared to small farms. In contrast, when looking at adoption of drought tolerant corn, there was no evidence of farm size playing significant a role (McFadden, Smith, Wechsler, & Wallander, 2019). There is an opportunity to encourage carbon sequestration through adoption enhanced root trait corn varieties as a simple straight forward practice, the key is to limit other cumbersome requirements.

Gramig (2012) addresses two important issues of agricultural soil carbon sequestration, specifically around conservation tillage. The first is the issue that adopting a practice and receiving payment for carbon sequestration requires a long-term commitment. It is important for any policy to avoid reversal, where the practice is abandoned, and carbon is released back to the atmosphere. The second is structuring carbon payments under the phase of soil carbon saturation. After 20+ years of conservation tillage, soil carbon stocks are predicted to reach carbon saturation. At that point these agricultural soils would no longer be offsetting new emissions but holding onto previously offset emissions.

The authors propose a few designs for supplying long-term ecosystem services. A relevant option is through the use of the relative profitability condition.

$$\sum_{t=0}^{\infty}(gross\ margin^{t})\delta^{t} < \sum_{t=0}^{\infty}(gross\ margin^{t} + offsetpayment^{t})\delta^{t}$$

where $gross\ margin^{t}$ gives the profitability for each time period t and $offsetpayment^{t}$ gives the amount of payment that can be received after adopting no-till. When this condition holds, farmers will choose the more profitable option to supply the ecosystem service. Root enhanced traits would produce a similar circumstance.

A choice experiment is used to assess Corn Belt farmer's willingness to accept payment to adopt conservation tillage (reduced and no-till) practices to sequester carbon as a mechanism to mitigate climate change under international agreement protocols (Gramig & Widmar, 2018). Results are consistent with intuition, farmers that have not yet adopted conservation tillage are the most resistant to changing their tillage practices, displaying a willingness to accept $40 per acre to switch from conventional tillage, while those that have already adopted reduced tillage would not need monetary incentive to switch to no-till. Switching from conservation tillage to conventional tillage would inherently release GHG previously stored, negating any offset achieved. To prevent a delay in GHG emissions, and succeed in true sequestration, a long-term contract may be necessary. The choice experiment reveals that farmers negatively value option limits. Farmers would be willing to accept $10.57 per acre for being locked into a multi-year contract.

Another primary constraint is the accounting for carbon sequestration is highly uncertain. Springborn et al. (2013) evaluate effectiveness of the margin of safety approach to provision of ecosystem services. They empirically examine the efficiency of it in application to crediting greenhouse gas offsets in agriculture. Depending on how this approach is used and the context it is used in, there is still overestimation and underestimation of sequestration.

Part of the challenge in accounting for greenhouse gas emissions or sequestration is the lack of knowledge of soil carbon cycling and the high level of variability of agricultural land. Land-use based emission reductions and carbon storage options are highly uncertain in examining mitigation strategies (Rogelj et al., 2018). Paustian et al. (2016) provide a strategy for dealing with this uncertainty. The authors cite that the more uncertain carbon storage rate is for a particular activity, the greater the discount that should be applied to its offsetting power. This discounting encourages efforts to decrease uncertainty through research and monitoring. As programs for agricultural soil carbon sequestration are first implemented, less offset power should be provided for the same cost to any corporation intending to buy carbon credits. As groups invest in improving accuracy of soil carbon storage accounting more offset credits may be available.

CHAPTER 4 METHODOLOGY

4.1 Optimizing Annual Gross Margin

The benefits of Category 1, as described in the previous section, are strictly based on annual profits. This section aims to evaluate the margin of costs and price that influence the decision to adopt corn varieties with enhanced root traits. Although several mechanisms of Category 1 benefits are possible to implement, the result will show up either to reduce variable costs or to increase total revenue. The marginal effects of these on profits are examined.

First, the effect of changes to price and cost are examined. A gross margin optimization model is used to demonstrate resulting pecuniary benefits. Constraints include land, production, and sales. Then the model is expanded to include expected drought tolerance impact on water demand considering irrigation water cost and availability. Multiple hypothetical varieties of corn with varying traits that differ in cost and water requirements are compared to a baseline variety currently available on the market.

The model begins with standard form of gross margin.

Maximize

$$Total\ Gross\ Margin = Total\ Revenue - Variable\ Cost$$

To evaluate the margin of effects of corn water demand the following modified gross margin model was developed.

Maximize

$$GM_i = \sum_{i=0}^{2}(P_i * CornSales_i) - \sum_{i=0}^{2}(VC_i * AcreS_i) - (CW * WP)$$

Subject to the following constraints

$$\sum_{i=0}^{2}(AcreS_i) \leq Total\ acres\ available\ for\ the\ average\ farm\ in\ each\ state$$

$$\sum_{i=0}^{2}(Yield_i * AcreS_i) - CornSales_i \geq 0$$

$$\sum_{i=0}^{2}(W_i * AcresS_i) - WP \leq 0$$

$$\sum_{i=0}^{2}(W_i * AcresS_i) \leq Total\ acrefeet\ of\ water\ available$$

Where

Decision Variables	**Description**
$i =$	index representing individual corn seed varieties $(i = 0, 1, 2)$
$GM_i =$	gross margin for variety *i*
$AcreS_i =$	number of acres growing variety *i*
$CornSales_i =$	bushels of corn sold of variety *i*
$WP =$	Acre-feet of water purchased

Objective Function and Constraint Variables	**Description**
$Yield_i =$	bushels per acres of corn harvested for variety *i*
$P_i =$	price at market for a bushel of variety *i*
$VC_i =$	variable cost of variety *i* less the cost of irrigation water
$CW =$	cost per acre-foot of irrigation water
$W_i =$	Acre-feet of water demanded per acre for variety *i*

The gross margin maximization model is solved using linear programming to estimate the producer decision to choose between three varieties of corn with differing levels of enhanced root traits. The linear objective function for total gross margin is calculated as: Total revenue is the price per bushel of corn multiplied by the bushels sold across all varieties, Total variable cost is the sum of the unique variable cost for each variety multiplied by the number of acres planted with each variety. The results of running the model will provide a few key insights.

Simplex algorithm linear programing solves for the optimal solution, giving levels of product mix to maximize or minimize the objective function. Constraints are determined by the level of resources available. In this case the objective function maximizes gross margin and is constrained by resources of available land and irrigation water cost and availability. The basis matrix includes the coefficients of all relevant decision variables and slack from the objective and constraints that are part of the explicit solution. The initial feasible basis is transformed through several iterations. The model includes variables based on their reduced cost, which is the impact of including each variable on the optimal solutions. A negative reduced cost is the marginal cost of that variable and acts to reduce the objective and is thus excluded from the optimal solution. A positive reduced cost is the marginal benefit of that variable on the objective. The optimal solution is found when all of the variables included in the basis have positive reduced cost.

The process of iteratively updating the basis also reveals what would change the optimal solution. The shadow price gives the willingness to pay to change the capacity available of the constraint. It shows how the optimum of the objective changes as the constraint changes. The shadow price is determined by the level of resource used by each unit of decision variables given the capacity of the constraints. The allowable increase and allowable decrease of each constraint indicate the point at which the product mix would change and give a new optimal solution.

Keeping the objective and all but one constraint consistent and systematically adjusting one constraint reveals a finite number of possible solutions to the product mix. Using the information from the allowable increase and allowable decrease shows the point at which different variety mixes are selected. Changing water availability is a useful tool to extract the full range of decisions in a water constrained future.

4.2 Data

The greatest challenge of this study was overcoming a lack of data and inconsistent levels of data. The primary source of land acres used for corn, price, and cost data was from a *Special Report: Cost and Returns Data Product* compiled by the US Department of Agriculture Economic Research Service (ERS) using 2016 Agricultural Resource Management Survey data and other sources. ERS employee William McBride pulled data for specific states out of a regionally averaged report. States of interest include Colorado, our home state, Iowa, the top producer of corn, Kansas and Nebraska, which had the highest adoption rates of drought tolerant corn that is on the market now (McFadden, Smith, Wechsler, & Wallander, 2019).

Averaged data for each state includes operating costs: seed, fertilizer, chemicals, custom operations, fuel, lube, and electricity, repairs, purchased irrigation water, and interest on operating inputs; yield (bushels per planted acres), price, enterprise size (planted acres), percent of acres irrigated or dryland. Allocation overhead costs were not used.

The first issue is that this data was averaged for irrigated and dryland. Improvements for future studies could be made with more precise data for each state separating irrigated and dryland costs. Iowa reports 0% of the planted acres as irrigated. This allowed for direct analysis of Iowa from this single dataset. For Colorado, Kansas, and Nebraska other publicly available data were utilized to calculate costs for the differing production methods to account for the higher costs of irrigation and varying levels of yield. For each state two ratios were calculated one for irrigated operating costs to dryland operating costs and a second for irrigated yield to dryland yield. Along with these calculated ratios, the total operating costs per acre and the percent of dryland to irrigated land from the original ERS data set were used to calculate the per acre dryland operating costs and yield and the irrigated land operating cost and yield.

The data available for each state was presented in slightly different format and levels. Here the calculation process for each state is described:

Colorado State University Extension, Agriculture and Business Management section provides Crop Enterprise Budgets for every year, multiple regions, crops, and production practices. Regions include Northeast, Southeast, South Platte Valley, and Western. Production practices include irrigated, furrow irrigation, reduced till sprinkler irrigation, and dryland reduced till. Operating cost and yield were averaged for each region and production practice for 2015, 2016, and 2017. Dryland was kept separate, while all the irrigated regions were then averaged together.

Kansas State University provides Farm Management Guides developed by the Department of Agricultural Economics in the Agmanager.info website. They provide Corn Cost Return Budgets for irrigated and non-irrigated farms only for 2019. Regions include Southwest, North Central, and Northwest, which have both irrigated and non-irrigated farms and Southeast, South Central, and Northeast are only non-irrigated farms. Typical yield and typical operating costs were averaged together for irrigated and non-irrigated farm regions.

University of Nebraska Lincoln Extension and Institute of Agriculture and Natural Resources hosts CropWatch website. There, the Nebraska Crop Budgets are provided for each year and for dryland and irrigated corn. For both irrigated and dryland nine budgets are presented, each is different based on corn variety traits, production practices, regions, and yield. It was possible to use 2016 to be consistent with the original USDA data. Again, operating costs and yield were averaged for irrigated and dryland corn.

Each state’s water cost and demand data came from a consistent source. The USDA National Agricultural Statistics Service conducted the 2012 Census of Agriculture and provides the 2013 Farm and Ranch Irrigation Survey. Two tables were used: Table 14 Expenses for Irrigation Water from Off-Farm Suppliers for 2013 and Table 36 Estimated Quantity of Water Applied and Primary Method of Distribution by Selected Crops Harvested in the Open for 2013. These tables provided average cost per acre-foot in dollars, total irrigated acres harvested, total irrigated farms, and average acre-feet applied per acre, which were used to calculate average acres of irrigated farms and total cost of irrigation water per acre.

The total acre-feet of water available was calculated with the average acre-feet applied per acre and the average enterprise size to give the expected water availability for the entire farm. The total amount of water available was changed to simulate drought scenarios.

Another limitation was the irregularity of fertilizer costs. Average fertilizer costs were not available for varying production practices and regions. Future studies that have ability to survey fertilizer use would be a useful extension. Summary statistics of data calculated as descried are provided below in figures 6 and 7 and tables 1, 2, and 3.

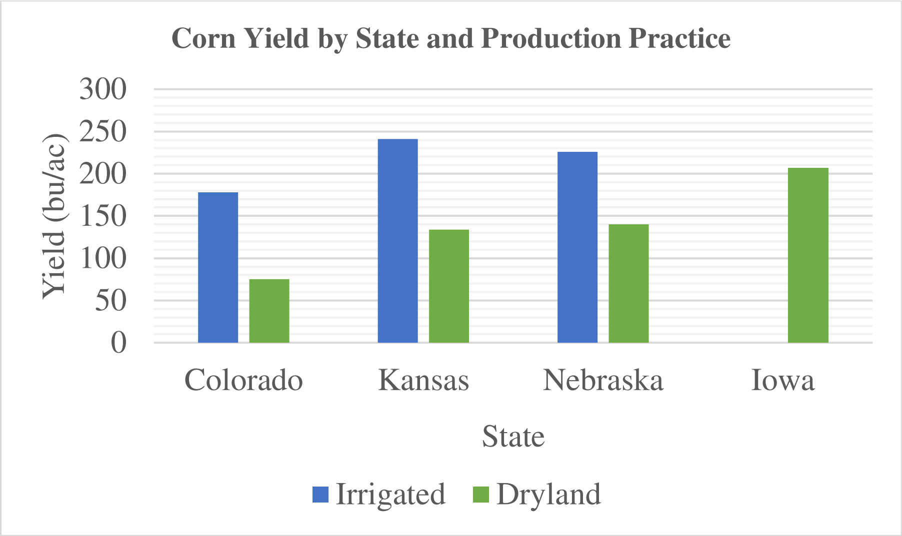

Figure 6. *Corn yield by state and production practice.*

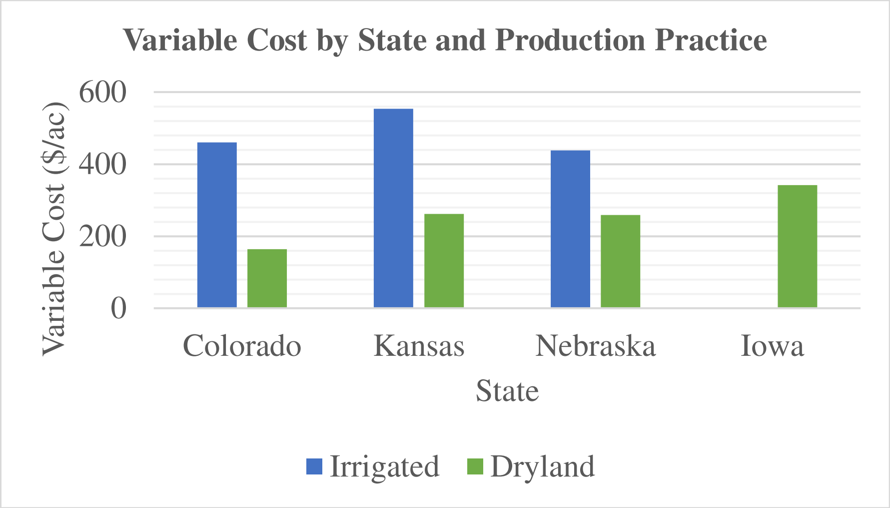

Figure 7. *Variable cost by state and production practice.*

Table 1. *Summary statistics of states in study.*

	Units	**Colorado**	**Kansas**	**Nebraska**	**Iowa**
Total Production in 2016 [1]	Bushels	185,592,354	693,862,078	1,694,898,568	2,583,967,870
Rank in US[2]		16	7	3	1
Avg Enterprise size[3]	Acres	371	391	350	292
Avg Yield[3]	Bushels/acre	134	148	189	207
Price[3]	Dollars/ bushel	3.36	3.18	3.31	3.30
Irrigation[3]	Percent of acres	57%	13%	57%	0%
Dryland[3]	Percent of acres	43%	87%	43%	100%
Drought Tolerant Corn Available on Market[4]	Percent of acres	20%	39%	42%	16%

Table 2. *Summary statistics of irrigated corn farms in study.*

		Irrigated		
	Units	**Colorado**	**Kansas**	**Nebraska**
Average acre-feet of irrigated water applied per acre[5]	Acre-feet per acre	1.6	1.3	1
Average Cost of Irrigation Water[5]	Dollars/ acre-foot	16.96	47.16	42.19
Total Cost of Irrigation Water[6]	Dollars/ acre	27.14	61.31	42.19
Total Variable Costs per acre[6]	Dollars/ acre	459.92	554.07	438.16
Total Variable Costs per acre Less Irrigation Water Purchase Costs[6]	Dollars/ acre	432.78	492.76	395.97
Yield[6]	Bushels/ acre	178.16	241	226

Table 3. *Summary statistics of dryland corn farms in study.*

		Dryland			
	Units	**Colorado**	**Kansas**	**Nebraska**	**Iowa**
Total Variable Costs per acre[6]	Dollars per acre	163.96	261.72	258.65	342.43
Yield[6]	bushels per acre	75	134	140	207

1. USDA National Agricultural Statistics Survey, Quick Stats
2. USDA ERS, Farm Income and Wealth Statistics / Cash receipts by commodity State ranking
3. Special ERS Cost and Returns data product prepared by William McBride
4. McFadden, Smith, Wechsler, & Wallander, 2019
5. USDA, National Agricultural Statistics Service, 2013 FRIS - Entire Farm Data 2012 Census of Agriculture
6. Data sources cited above and original calculations

Additional summary statistics of operation size breakdown are provided in figures 8-12.

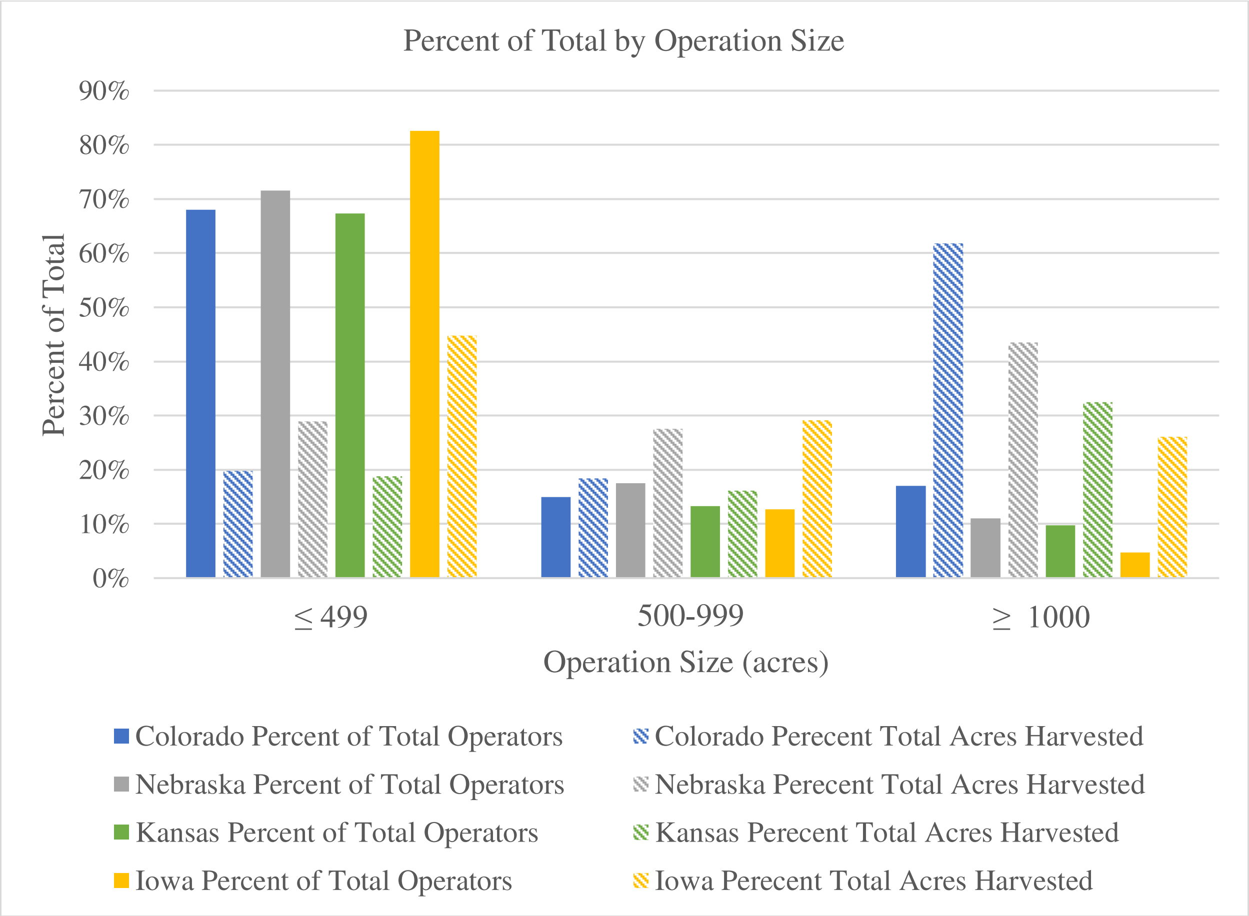

Figure 8. *Percent of total by corn farm operation size and for acres harvested for four study states. Source:2017 Census of Agriculture - State Data USDA, National Agricultural Statistics Service*

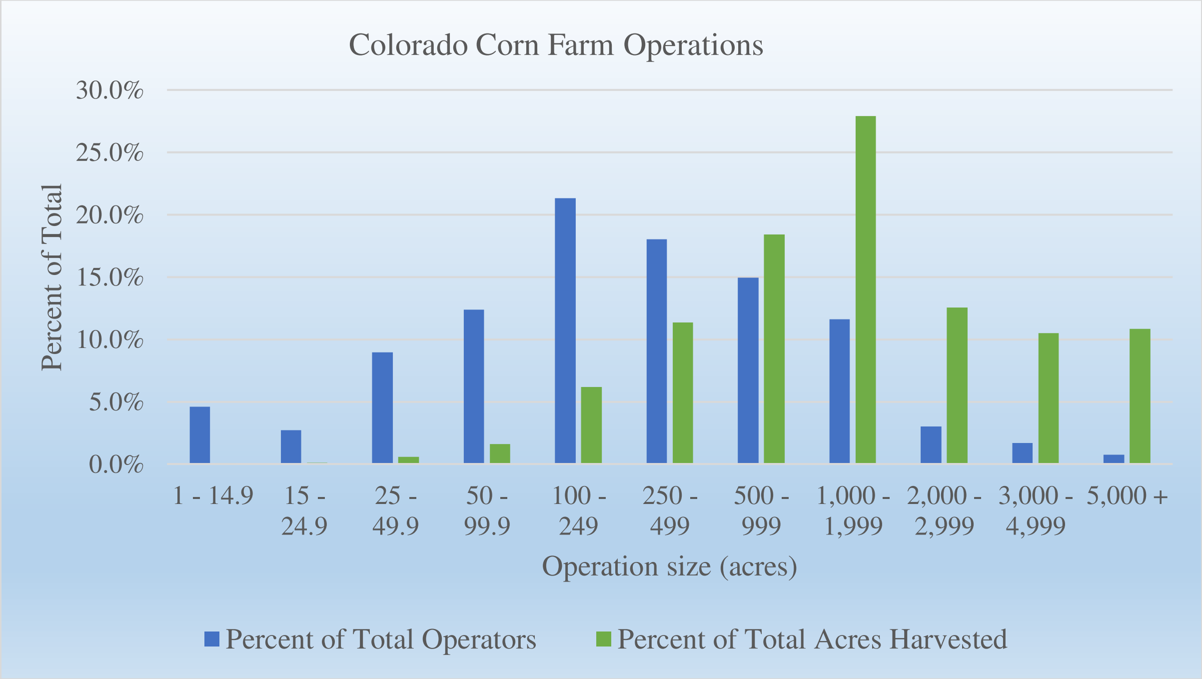

Figure 9. *Colorado corn farm breakdown by operation size and acres harvested.*
Source:2017 Census of Agriculture - State Data USDA, National Agricultural Statistics Service

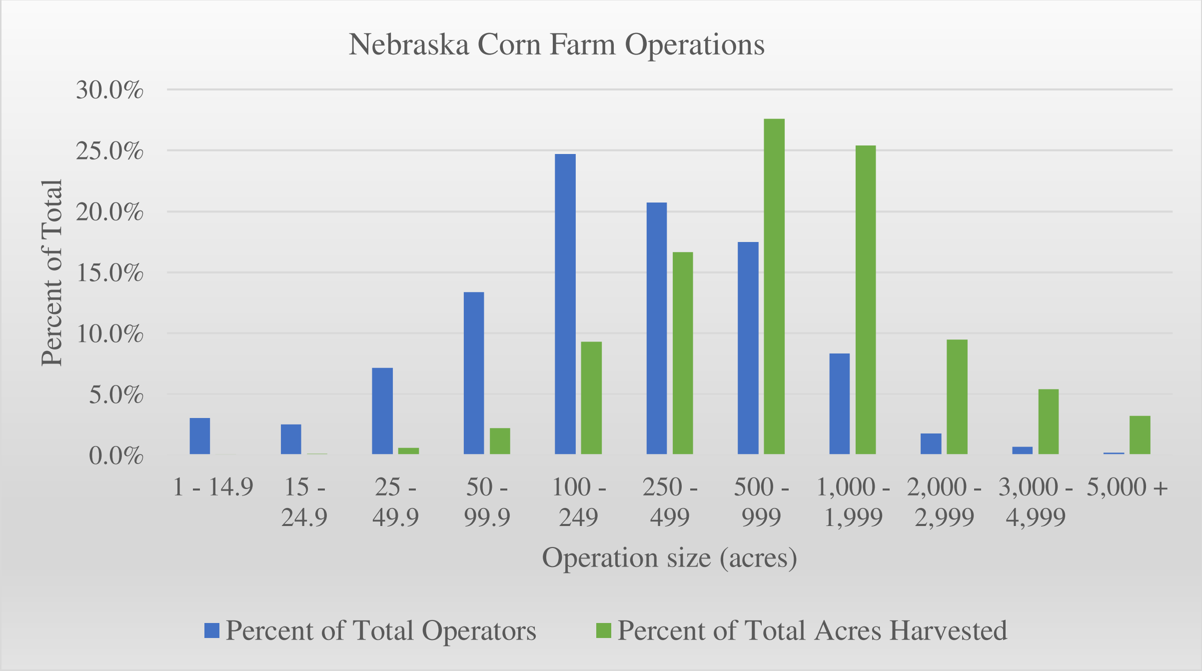

Figure 10. *Nebraska corn farm breakdown by operation size and acres harvested.*
Source:2017 Census of Agriculture - State Data USDA, National Agricultural Statistics Service

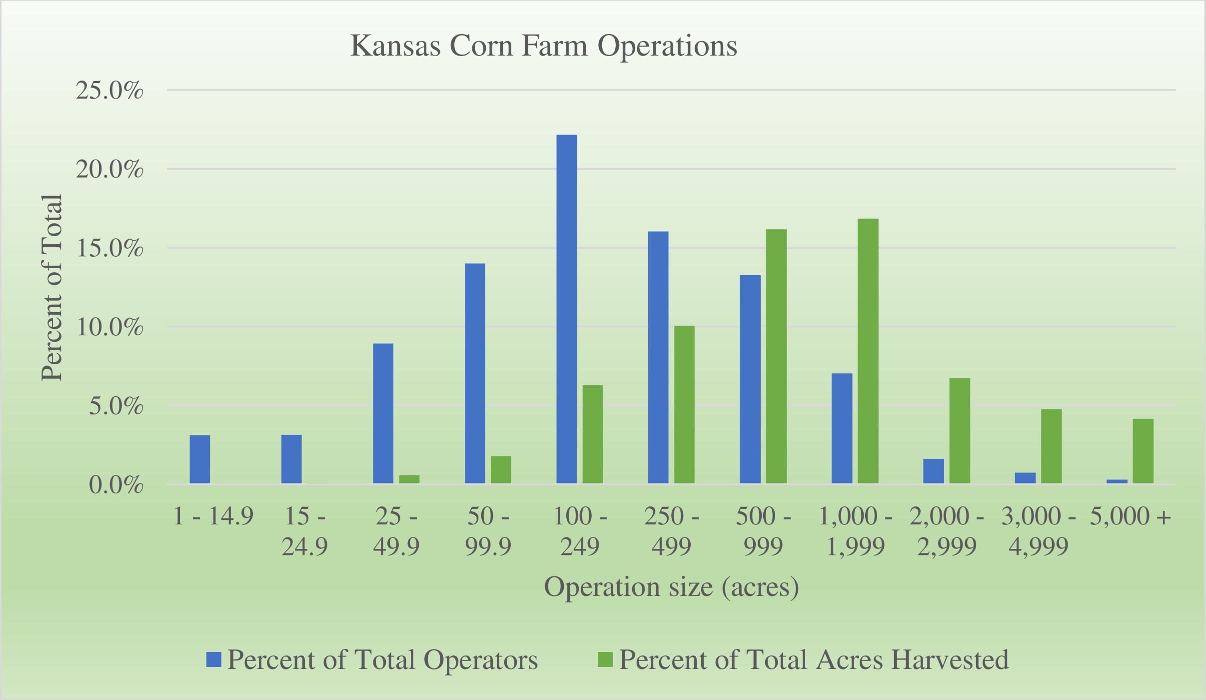

Figure 11. *Kansas corn farm breakdown by operation size and acres harvested.*
Source:2017 Census of Agriculture - State Data USDA, National Agricultural Statistics Service

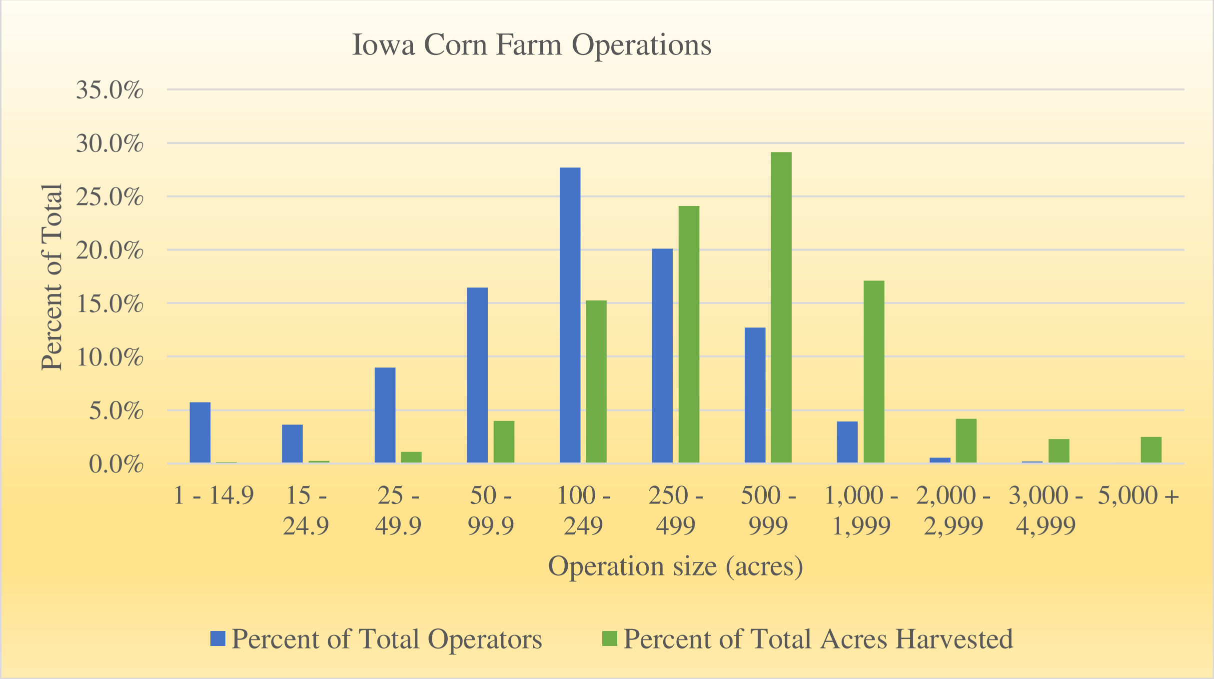

Figure 12. *Iowa corn farm breakdown by operation size and acres harvested.*
Source:2017 Census of Agriculture - State Data USDA, National Agricultural Statistics Service

CHAPTER 5 RESULTS AND DISCUSSION

Two profit models are used to evaluate the impact of several policy and trait adoption scenarios. First, a model of irrigated corn gross margin evaluates three scenarios for Colorado, Nebraska, and Kansas. Then dryland farms are studied under three scenarios for Colorado, Nebraska, Kansas, and Iowa.

The results aim to elicit the impact of changes to policy and the market regarding adoption of carbon sequestration and conservation practices with positive externalities provided by corn root traits. These models consider the average water availability and use and average variable cost to the average farm in each state. Larger or smaller farms will have differing costs and constraints, differing land qualities will have different input requirements and yield potentials. Not every farm will be captured. These models also assume producers have varying levels of information. Ex-ante analysis of new varieties of corn with enhanced root traits inherently requires analysis of hypothetical scenarios. Several possible scenarios are used to shock the model to determine the impact on profitability and the decision to choose different varieties of corn.

The corn variety on the market (i=0) is compared against two hypothetical new varieties. The market variety is also an average representative variety, requiring and producing the ‘typical’ inputs and yield. As land and productions practices vary in real life, the higher and lower bounds of inputs and yield are not necessarily captured.

The first hypothetical variety (i=1) represents an improved version of what is already on the market. The second hypothetical variety (i=2) moves toward the ideal phenotype goal of the ROOTS project.

The first set of scenarios (1, 2, and 3) involves selection of corn varieties on irrigated acreage. Scenario 1 sets a baseline, demonstrating a plausible early stage reality in which producers do not realize any private benefits of enhanced root genetics, but only positive externalities contributing to a public good through carbon sequestration. Here and throughout every scenario, higher levels of carbon sequestration come at a higher cost for those varieties. A rational decision maker is not expected to pay more without a private benefit. In scenarios 2 and 3 the farmer is effectively able to substitute away from irrigation water as a physical input to the genetic input of drought tolerance furnishing a valuable private benefit.

The second set of scenarios (4, 5, and 6) involves selection of corn varieties on dryland acreage. Scenario 4 again sets a baseline of higher cost varieties providing a public good but lacking private benefits. Scenario 5 tests the decision when loss protection is an available benefit, diminishing down-side risk. In Scenario 6, the adoption decision is revealed under yield increases.

The scenarios are based on market trends and interviews with farmers. While they do not represent every reality, the purpose of the following analysis is to demonstrate the need for diverse economic mechanisms to encourage adoption of sustainable varieties of corn.

5.1 Irrigated Scenarios

The base model below is used for each state's irrigated farms. Three scenarios are applied to the model in Excel using the Solver function for simplex linear programming.

Maximize

$$GM_i = \sum (P_i * CornSales_i) - \sum (VC_i * AcreS_i) - (CW * WP)$$

Subject to the following constraints

$$\sum AcreS_i \leq Total\ acres\ available\ for\ the\ average\ farm\ in\ each\ state\ (enterprise\ size)$$

$$\sum(Yield_i * AcreS_i) - CornSales_i \geq 0$$

$$\sum(W_i * AcresS_i) - WP \leq 0$$

$$\sum(W_i * AcresS_i) \leq Total\ acrefeet\ of\ water\ available$$

Table 4. *Irrigated corn farm parameters by state.*
Data for i=0 sourced as described in previous chapter

Irrigated Model Parameters Corn variety currently on the market (*i*=0)			
Variable	**Colorado**	**Kansas**	**Nebraska**
P_0	3.36	3.18	3.31
VC_0	432.78	492.76	395.97
CW	16.96	47.16	42.19
Enterprise Size	371	391	350
$Yield_0$	178	241	226
W_0	1.6	1.3	1.0
WP (Optimal acre-feet of water for entire enterprise)	593.6	508.3	350.0

Scenario 1, with conditions presented in table 5, demonstrates a no action possibility where producers have imperfect information. Producers see a higher price for varieties 1 and 2 and have no other information about changes to inputs or yield. Costs for drought tolerant corn varieties incur a \$10 premium on average in the U.S., as found in the USDA report on drought tolerant corn adoption (McFadden, Smith, Wechsler, & Wallander, 2019). Costs for the second hypothetical variety were increased another \$10 to give a range to compare.

Table 5. *Scenario 1 conditions*

Scenario 1: Irrigated – Normal conditions, higher cost for enhanced root trait varieties	
Policy or Phenotypic Shock	
Yield	Constant
Price	Constant
Variable Cost	Increase by \$10 (*i*=1) and \$20 (*i*=2)
Water Use	Constant

This scenario is useful to explore carbon sequestration policy. Here the benefits of varieties 1 and 2 have no known direct monetary value to the producer. Hypothetical varieties 1 and 2 provide significantly greater carbon sequestration than Variety 0.

Results of scenario 1 follow expectations presented in Table 6. When producers are faced with higher seed costs without other changes to inputs or revenue, the lowest-cost varieties are always chosen. The producer will not choose to sequester carbon through the use of Variety 1 or 2. Even this simple case reveals a few insights from the sensitivity report generated by Excel.

Table 6. *Results for Scenario 1 in Colorado, Kansas, and Nebraska*

Colorado Optimal Gross Margin = $51,258.84						
	Level of Activity	**Price**	**Shadow Price**	**Variable Cost**	**Allowable Increase**	**Allowable Decrease**
Variety 0	371	3.36	3.36	-432.78	Infinite	10
Variety 1	0	3.36	3.42	-442.78	10	Infinite
Variety 2	0	3.36	3.47	-452.78	20	Infinite
Kansas Optimal Gross Margin = $83,013.99						
Variety 0	391	3.18	3.18	-492.76	Infinite	10
Variety 1	0	3.18	3.22	-502.76	10	Infinite
Variety 2	0	3.18	3.26	-512.76	20	Infinite
Nebraska Optimal Gross Margin = $108,465.00						
Variety 0	350	3.31	3.31	-395.97	Infinite	10
Variety 1	0	3.31	3.35	-405.97	10	Infinite
Variety 2	0	3.31	3.39	-415.97	20	Infinite

The most obvious result is that a change in the variable cost of $10 and $20 for Veriety 1 and 2 respectively will change the producer’s decision. A technology rebate from the seed company or government payment in those amounts respectively would change the producer’s decision. The shadow price for Variety 1 and 2, provides a benchmark and range for price premiums for each bushel. That is, a producer would choose a different variety of corn if they received these higher prices, as indicated by each shadow price. In each state a farmer would grow Variety 2 if they knew they would receive a price premium of $0.11 more per bushel in Colorado and $0.08 in Kansas and Nebraska for growing corn that sequesters more carbon than the currently available variety. This model could be adjusted to fit any specific farm and market scenario of interest. Various levels of price and costs could be examined further to elicit exact policy impacts on producer decisions.

Scenario 2 conditions presented in Table 7 demonstrate changes to the information that a producer has and the environmental conditions faced. During a hypothetical drought, water availability is decreased systematically to reveal several choice outcomes. The producer also has perfect information in this scenario, they know how much water each variety requires for optimal yield at harvest, how much water will be available throughout the season, the price they will get at market for a bushel of corn, and total variable costs per acre.

Table 7. *Conditions for Scenario 2*

Scenario 2: Irrigated during Drought - Higher cost for enhanced root trait varieties, water required by each variety varied, water availability limited	
Policy or Phenotypic Shock	
Yield	Constant
Price	Constant
Variable Cost	Increase by $10 ($i$=1) and $20 ($i$=2)
Water Use	Water use decrease by A)10% (i=1), B) 25% (i=2)
Water Availability	Water availability decrease from optimal level

An important limitation of this model is that the variability of water application required throughout different growth stages is not captured. Instead the water quantity available is for use over a whole growing season. While timing of water application is important in real production, it is ignored to simplify the model and analysis of results. Future studies with more data should consider such impacts.

Scenario 3 is similar: producers know the drought conditions they face and the water requirement of each variety. The difference from Scenario 2 is that the enhanced root trait varieties have improved drought tolerance, requiring even less water, with details presented in Table 8. Scenarios 2 and 3 will be discussed together, with each state separated.

***Table 8**. Conditions for Scenario 3*

<u>Scenario 3</u>: Irrigated during Drought - Higher cost for enhanced root trait varieties, water required by each variety varied, water availability limited	
Policy or Phenotypic Shock	
Yield	Constant
Price	Constant
Variable Cost	Increase by \$10 (*i*=1) and \$20 (*i*=2)
Water Use	Water use decrease by A) 35% (*i*=1), B) 50% (*i*=2)
Water Availability	Water availability decrease from optimal level

5.1.1 Colorado

Results of producer decisions under scenario 2 are presented in Table 9.

***Table 9.** Results for Scenario 2 in Colorado*

Colorado							
Scenario 2A **Optimal Gross Margin = \$48,166.30**							
	Water Needed	**Level of Activity**	**Price**	**Shadow Price**	**Variable Cost**	**Allowable Increase**	**Allowable Decrease**
Variety 0	1.60	137	3.36	3.36	-432.78	28.43	3.33
Variety 1	1.44	0	3.36	3.37	-442.78	2.00	Infinite
Variety 2	1.20	234	3.36	3.36	-452.78	13.22	5.00
Water Available	-	500	-	33.04	-	93.60	54.80
Water Purchased	-	500	-	-	-16.96	16.96	33.04
Scenario 2B **Optimal Gross Margin = \$46,334.88**							
	Water Needed	**Level of Activity**	**Price**	**Shadow Price**	**Variable Cost**	**Allowable Increase**	**Allowable Decrease**
Variety 0	1.60	0	3.36	3.52	-432.78	28.43	Infinite
Variety 1	1.44	0	3.36	3.47	-442.78	19.06	Infinite
Variety 2	1.20	371	3.36	3.36	-452.78	Infinite	15.88
Water Available	-	445	-	104.12	-	0.20	445.00
Water Purchased	-	445	-	-	-16.96	16.96	104.12

Colorado's optimal water availability under normal efficient conditions is 593.6 acre-feet for the average 371-acre farm with a gross margin of $51,258.84. Both Scenario 2A and 2B water needed was decreased by 10% and 25% for varieties 1 and 2 respectively.

Water availability was changed systematically after evaluation of the Excel produced sensitivity report. As seen in Table 9 above the columns labeled "Allowable Increase" and "Allowable Decrease" indicate how much each constraint can change before the product mix changes. Changing water availability is a useful tool to extract the full range of decisions in a water constrained future.

When water efficiency and cost are as presented in both Scenario 2A and 2B, and when there is at least 593.6 acre-feet of water available the producer will always choose to only plant Variety 0, which is the result in Scenario 1. As soon as the water availability dips below 593.6 acre-feet, the producer shifts away from only Variety 0 and includes a second variety in the mix. That new mix of varieties will be maintained when the water availability is strictly less than 593.6 acre-feet and strictly greater than 445.2 acre-feet. This range is determined through the allowable increase and allowable decrease of the constraint labeled "Water Available".

In Scenario 2A, available water was decreased to 500 acre-feet using the method stated above to extract a new product mix between varieties 0 and 2. The available land and budget are split between the cheapest variety and the most drought-tolerant variety. The shadow price of Water Available of $33.04, is what a producer would pay to relax that constraint by increasing water availability by 1 acre-foot. They would pay this cost for each acre-foot of water up until the allowable increase of 93.6 acre-feet of water, which would bring them back to optimal levels of water and optimal product mix. This is reflected in the allowable increase in the cost of water purchased.

The allowable decrease of 54.8 acre-feet of water available is the point at which the product mix would change again. Scenario 2B shows the new product mix at the next margin. As water availability dips below that allowable decrease as demonstrated in Scenario 2B, the producer switches and only grows the most drought-tolerant variety. Again, this mix stays constant until there is no water available as shown by the allowable decrease of water available of 445 acre-feet.

This choice comes at a big cost, losing $4,913.96, or almost 10% of their gross margins from optimal levels. If water availability decreases further, the land constraint is non-binding, the producer stops using all of their land in production. Another flaw of this model is that other crops are not considered, which may be cheaper to grow and require less water. In that case, the producer may shift entirely away from corn. Below 445 acre-feet of available water, the producer is willing to pay $104.12 for an extra unit of water.

Analysis of variable cost between 2A and 2B show how much a producer is willing to pay for extra drought tolerance traits. In both 2A and 2B, the allowable increase for Variety 0, the least drought-tolerant variety, is $28.43. In the limited water scenarios, the producer would not choose more of the least drought-tolerant variety unless its variable cost decreased to less than $404.35 per acre.

Conversely in Scenario 2A, if Variety 1 was $2 less, at $440.78 per acre, the producer would shift and produce more of this medium tolerant variety, putting it at a total of $8 higher cost than the currently available variety. The allowable decrease of Variety 2 of $5 demonstrates the value of this level of drought tolerance. An increased cost of $25 more for 25% more drought tolerance than the market available variety would keep the same product mix at the level of water scarcity.

Scenario 2B gives a tighter picture with fewer feasible options. The producer would not choose the varieties requiring more water until they were less costly than what is currently available. Only the most drought-tolerant variety would be grown until its cost increased $35.88 more than the cheapest variety.

In Scenario 3A, 3B, and 3C, the water requirement was decreased by 35% and 50% for varieties 1 and 2 respectively. The results are provided in Table 10.

Table 10. *Results for Scenario 3 in Colorado*

Colorado							
Scenario 3A Optimal Gross Margin = $51,125.53							
	Water Needed	**Level of Activity**	**Price**	**Shadow Price**	**Variable Cost**	**Allowable Increase**	**Allowable Decrease**
Variety 0	1.60	204	3.36	3.36	-432.78	13.33	0.50
Variety 1	1.04	167	3.36	3.36	-442.78	0.50	4.00
Variety 2	0.80	0	3.36	3.39	-452.78	5.71	Infinite
Water Available	-	500	-	0.90	-	93.60	114.16
Water Purchased	-	500	-	-	-16.96	16.96	0.90
Scenario 3B Optimal Gross Margin = $51,072.60							
	Water Needed	**Level of Activity**	**Price**	**Shadow Price**	**Variable Cost**	**Allowable Increase**	**Allowable Decrease**
Variety 0	1.60	0	3.36	3.36	-432.78	13.33	0.50
Variety 1	1.04	371	3.36	3.36	-442.78	0.50	4.00
Variety 2	0.80	0	3.36	3.39	-452.78	5.71	Infinite
Water Available	-	386	-	0.90	-	207.60	0.16
Water Purchased	-	386	-	-	-16.96	16.96	0.90
Scenario 3C Optimal Gross Margin = $48,951.63							
	Water Needed	**Level of Activity**	**Price**	**Shadow Price**	**Variable Cost**	**Allowable Increase**	**Allowable Decrease**
Variety 0	1.60	0	3.36	3.43	-432.78	13.33	Infinite
Variety 1	1.04	13	3.36	3.36	-442.78	33.59	4.00
Variety 2	0.80	358	3.36	3.36	-452.78	5.71	25.84
Water Available	-	300	-	24.71	-	85.84	3.20
Water Purchased	-	300	-	-	-16.96	16.96	24.71

Colorado’s optimal water availability of 593.6 acre-feet for the average farm, was decreased to 500 acre-feet in Scenario 3A, 386 acre-feet in 3B, and 300 acre-feet in 3C. The acre-feet of water available was varied according to results of the allowable increase and decrease of that constraint. The product mix resulting in 3A would be consistent as water availability changes from less than 593.6 acre-feet to more than 385.8 acre-feet. Scenario 3B is useful to show the very end of that range. In Scenario 3C, the water available is reduced to the next product mix and will continue up until 296.8 acre-feet as given by the allowable decrease of 3.2 acre-feet.

The extra water efficiency produces a different mix than Scenario 2A. In Scenario 3A the two less expensive varieties are produced. A change in variable cost of just $0.50 per acre of either Variety 0 or 1 would create a different product mix. At this level, Variety 2, the most expensive and most drought tolerant variety would not be included in the mix until market price increased by $0.03 a bushel or variable cost decreased by $5.71 per acre. Looking closer at 3C, drought tolerance becomes a very valuable trait, with the producer willing to pay up to $45.84 more for Variety 2 than Variety 0. This is a difference of over 10% higher cost, for 50% more drought tolerance under water scarce conditions.

Greater drought tolerance also preserves the gross margin. Under the greatest water scarcity gross margin only decreases by 4% from the non-water scarce scenario, whereas in 2B with less water scarcity and less drought tolerant varieties, gross margin loss is at 10%. The water efficiency provided by the Varieties 1 and 2 reduce the impact of water scarcity. The producer is less willing to pay more for water, an extra unit of irrigation water is only worth another $0.90 in 3A and B and $24.71 in 3C, compared to Scenarios 2A at $33.04 and 2B at $104.12.

5.1.2 Kansas

Results for Kansas under Scenario 2 are presented in Table 11 and discussed below.

Table 11. *Results for Scenario 2 in Kansas*

Kansas							
Scenario 2A **Optimal Gross Margin = $82,894.65**							
	Water Needed	**Level of Activity**	**Price**	**Shadow Price**	**Variable Cost**	**Allowable Increase**	**Allowable Decrease**
Variety 0	1.30	365	3.18	3.18	-492.76	64.54	3.33
Variety 1	1.17	0	3.18	3.19	-502.76	2.00	Infinite
Variety 2	0.975	25	3.18	3.18	-512.76	4.67	5.00
Water Available	-	500	-	14.38	-	8.30	118.78
Water Purchased	-	500	-	-	-47.16	47.16	14.38
Scenario 2B **Optimal Gross Margin = $81,138.93**							
	Water Needed	**Level of Activity**	**Price**	**Shadow Price**	**Variable Cost**	**Allowable Increase**	**Allowable Decrease**
Variety 0	1.30	0	3.18	3.18	-492.76	64.54	Infinite
Variety 1	1.17	0	3.18	3.35	-502.76	40.72	Infinite
Variety 2	0.98	391	3.18	3.18	-512.76	Infinite	33.94
Water Available	-	381	-	212.96	-	0.23	Infinite
Water Purchased	-	381	-	-	-47.16	47.16	212.96

Kansas' optimal water availability is 508.3 acre-feet for the average 391-acre farm producing an optimal gross margin of $83,013.99. For Scenario 2A and 2B Variety 1 and 2 required 10% and 25% less water for optimal yield.

Using information from the allowable increase and decrease of water availability, that constraint is systematically changed to extract a new product mix. The first stage of water scarcity decreased water availability below the optimal level to 500 acre-feet of water. Here the gross margin only lost $119. Revenue was maintained with a new product mix, a majority of land was devoted to the least expensive variety, with the most expensive and most drought tolerant variety for the remaining land.

The margins are very tight in this scenario. If Variety 1 received a price premium $0.01 more than the market variety or if its variable cost were $2 lower, the product mix would change in favor of this variety. More Variety 2 would be grown if the variable cost decreased by $4.67. The shadow price for irrigation water availability is $14.38 at 500 acre-feet and $212.96 at 381 acre-feet, in Scenario 2B the producer would be willing to pay that much more to loosen this constraint and receive one extra unit of water.

Scenario 2B is a much more confined result, though the gross margin only decreases by 2%. The water constraint requires only Variety 2, so only the most water efficient variety is grown. The allowable increase of variable cost for Variety 0 and 1 are quite large, meaning that their costs would have to decrease by $65.54 and $40.72 respectively to be included in the production mix. Similarly, Variety 2 would not be excluded until the variable cost is $33.94 greater, putting the total value for the greatest drought tolerant trait $53.94 greater than the market available variety.

Impacts of greater drought tolerance are shown in the results in Table 12.

Table 12. *Results for Scenario 3 in Kansas*

Kansas							
Scenario 3A **Optimal Gross Margin = $87,493.99**							
	Water Needed	**Level of Activity**	**Price**	**Shadow Price**	**Variable Cost**	**Allowable Increase**	**Allowable Decrease**
Variety 0	1.30	0	3.18	3.23	-492.76	11.46	Infinite
Variety 1	0.85	391	3.18	3.18	-502.76	Infinite	0.80
Variety 2	0.65	0	3.18	3.18	-512.76	0.80	Infinite
Water Available	-	509	-	0	-	Infinite	178.61
Water Purchased	-	330	-	-	-47.16	25.18	4.12
Scenario 3B **Optimal Gross Margin = $87,451.14**							
	Water Needed	**Level of Activity**	**Price**	**Shadow Price**	**Variable Cost**	**Allowable Increase**	**Allowable Decrease**
Variety 0	1.30	0	3.18	3.24	-492.76	13.33	9.92 E+17
Variety 1	0.85	338	3.18	3.18	-502.76	66.09	0.80
Variety 2	0.65	53	3.18	3.18	-512.76	0.80	50.84
Water Available	-	320	-	4.12	-	10.40	65.85
Water Purchased	-	320	-	-	-47.16	47.16	4.12
Scenario 3C **Optimal Gross Margin = $85,756.15**							
	Water Needed	**Level of Activity**	**Price**	**Shadow Price**	**Variable Cost**	**Allowable Increase**	**Allowable Decrease**
Variety 0	1.30	0	3.18	4.15	-492.76	233.62	Infinite
Variety 1	0.85	0	3.18	3.45	-502.76	66.09	Infinite
Variety 2	0.65	385	3.18	3.18	-512.76	Infinite	50.84
Water Available	-	250	-	343.02	-	4.15	250.00
Water Purchased	-	250	-	-	-47.16	47.16	343.02

Scenarios 3A, 3B, and 3C include greater drought tolerance traits, with Variety 1 requiring 35% less water and Variety 2 requiring 50% less water than the market available variety. Here the results show an interesting difference from the outcome of Scenario 3 in Colorado. The cost of water for an acre-foot in Kansas is $30.20 greater than an acre-foot of water in Colorado. This higher cost of water changes the initial outcome when more drought tolerant varieties are available.

In Scenario 3A, the optimal quantity of water is available, but the greater cost for the drought tolerance trait is overcome by the efficient use of this expensive input. Reducing the need for costly water results in a 5% increase in gross margin of $4,480. Water availability becomes non-binding, reducing the shadow price of irrigation water to $0, the producer would not pay more for an extra unit of water. Variety 1 and 2 are in close competition: if Variety 1 were $0.80 more costly or if Variety 2 were $0.80 less, then the product mix would change.

Scenario 3B reduced the water available to make this constraint binding with a non-zero shadow price. Now the producer would be willing to pay an extra $4.12 to gain an acre-foot of water. The water efficiency of Variety 1 and 2 make them equally as competitive as in 3A. The new product mix under this constraint does not have a great impact on gross margin.

Scenario 3C creates such a strict constraint on water availability that the enterprise size is now non-binding. The producer does not use all of their land to grow corn, as in Colorado that choice to grow another crop falls outside this model. Here the shadow price of irrigation water is $343.02, a producer would be willing to pay this much more to loosen this constraint and have one more unit of water available.

The allowable decrease of variable costs for Variety 2 is $50.84. In this extreme drought scenario, a 50% increase in the drought tolerance trait from the market available variety is now worth $70.84. As loss of water availability forces the farmer to retire some acres from production, drought tolerance becomes increasingly valuable.

5.1.3 Nebraska

Results for Nebraska under Scenario 2 are presented in Table 13.

Table 13. *Results for Scenario 2 in Nebraska*

Nebraska							
Scenario 2A Optimal Gross Margin = $108,086.90							
	Water Needed	**Level of Activity**	**Price**	**Shadow Price**	**Variable Cost**	**Allowable Increase**	**Allowable Decrease**
Variety 0	1.00	310	3.31	3.31	-395.97	90.70	3.33
Variety 1	0.90	0	3.31	3.32	-405.97	2.00	Infinite
Variety 2	0.75	40	3.31	3.31	-415.97	9.45	5.00
Water Available	-	340	-	37.81	-	10.00	77.50
Water Purchased	-	340	-	-	-42.19	42.19	37.81
Scenario 2B Optimal Gross Margin = $104,155.13							
	Water Needed	**Level of Activity**	**Price**	**Shadow Price**	**Variable Cost**	**Allowable Increase**	**Allowable Decrease**
Variety 0	1.00	0	3.31	3.71	-395.97	90.70	Infinite
Variety 1	0.90	0	3.31	3.56	-405.97	56.42	Infinite
Variety 2	0.75	347	3.31	3.31	-415.97	Infinite	47.02
Water Available	-	260	-	400.60	-	2.50	Infinite
Water Purchased	-	260	-	-	-42.19	42.19	400.60

Nebraska's optimal water availability is 350 acre-feet for the average 350-acre farm with an optimal gross margin of $108,465.00. For Scenario 2A and B Variety 1 and 2 required 10% and 25% less water for optimal yield.

Scenario 2A sees a product mix of Variety 0 and 2 at just 10 acre-feet less than the optimal, with a small loss in gross margin of $379. The margin of costs that would change the mix in this scenario are narrow. The gross margin and product mix would change with an increase in per acre variable costs of Variety 0 of only $3.33, a decrease in cost of $2 for Variety 1, and an increase in cost of $5 for Variety 2.

Tightening the water availability in Scenario 2B, the land constraint becomes non-binding, with the producer not utilizing all available acres for corn and a loss to gross margin of $4,310. Though this quantity is similar to the loss of gross margin in Colorado under this scenario, Colorado's loss is about 10% of the optimal gross margin whereas Nebraska's loss is only 4% of the original optimal gross margin.

The producer would be willing to pay much more to loosen the water availability constraint in 2B than in 2A. A shadow price of $400.60 is how much more the producer would be willing to pay to have one extra unit of water available. In this water scarce scenario, the increase in drought tolerance of 25% less water requirement is now worth $67.02 more than the market available variety as given by the allowable decrease of variable cost of Variety 2.

Greater drought tolerance is examined in Scenario 3 for Nebraska, shown in Table 14.

Table 14. *Results for Scenario 3 in Nebraska*

Nebraska							
Scenario 3A **Optimal Gross Margin = $110,133.28**							
	Water Needed	**Level of Activity**	**Price**	**Shadow Price**	**Variable Cost**	**Allowable Increase**	**Allowable Decrease**
Variety 0	1.00	0	3.31	3.33	-395.97	4.77	Infinite
Variety 1	0.65	350	3.31	3.31	-405.97	Infinite	3.67
Variety 2	0.50	0	3.31	3.31	-415.97	3.67	Infinite
Water Available	-	350	-	0	-	Infinite	122.50
Water Purchased	-	228	-	-	-42.19	13.62	24.48
Scenario 3B **Optimal Gross Margin = $110,072.08**							
	Water Needed	**Level of Activity**	**Price**	**Shadow Price**	**Variable Cost**	**Allowable Increase**	**Allowable Decrease**
Variety 0	1.00	0	3.31	3.37	-395.97	13.33	Infinite
Variety 1	0.65	333	3.31	3.31	-405.97	89.63	3.67
Variety 2	0.50	17	3.31	3.31	-415.97	3.67	68.94
Water Available	-	225	-	24.48	-	2.50	50.00
Water Purchased	-	225	-	-	-42.19	42.19	24.48
Scenario 3C **Optimal Gross Margin = $105,738.30**							
	Water Needed	**Level of Activity**	**Price**	**Shadow Price**	**Variable Cost**	**Allowable Increase**	**Allowable Decrease**
Variety 0	1.00	0	3.31	4.69	-395.97	312.09	Infinite
Variety 1	0.65	0	3.31	3.71	-405.97	89.63	Infinite
Variety 2	0.50	340	3.31	3.31	-415.97	Infinite	68.94
Water Available	-	170	-	621.99	-	5.00	170.00
Water Purchased	-	170	-	-	-42.19	42.19	621.99

Scenarios 3A, 3B, and 3C include greater drought tolerance trait, with Variety 1 requiring 35% less water and Variety 2 requiring 50% less water than the market available variety. Here results are consistent with the outcome of Scenario 3A in Kansas influenced by the high price of water relative to Colorado. Scenarios 3A and 3B result in increased gross margin. In Scenario 3A the water availability is non-binding, with all land devoted to Variety 1. The shadow price of water is $0, as expected. The margin of variable cost between the 3 varieties is narrow. The product mix and gross margin would shift if the per acre variable cost of Variety 0 decreased by $4.77, if Variety 1 increased by $3.67, or if Variety 2 decreased by $3.67.

Decreasing the water available to just under what was used in 3A according to information from the allowable decrease, the results give a different picture. The product mix ix split between Variety 1 and 2 with the same difference in variable cost of $3.67 making the difference between them. Here the water constraint is binding, with a shadow price of $24.48: the producer would be willing to pay this much more for an extra unit of water.

A new product mix is obtained using the allowable decrease to adjust water availability. A nearly 50% decrease in water availability from optimal levels makes the land constraint non-binding with the farmer unable to profitably use all of their land for corn in Scenario 3C. Here all of the resources are devoted to Variety 2, the most water efficient variety. An increase in drought tolerance of 50% is now worth $88.94 more than the market available variety. The value of water in this extreme drought scenario given by the shadow price is now $621.99, the producer is willing to pay this much more to gain an extra unit of irrigation water.

5.2 Dryland Scenarios

The following base model is applied to all four state's dryland farms.

Maximize

$$GM_i = \sum(P_i * CornSales_i) - \sum(VC_i * AcreS_i)$$

Subject to the following constraints

$$\sum AcreS_i \leq Total\ acres\ available\ for\ the\ average\ farm\ in\ each\ state\ (enterprise\ size)$$

$$\sum(Yield_i * AcreS_i) - CornSales_i \geq 0$$

Table 15. *Dryland corn farm parameters by state*
Data for i=0 sourced as described in previous chapter

Dryland Model Parameters Corn variety currently on the market (i=0)				
Variable	**Colorado**	**Kansas**	**Nebraska**	**Iowa**
P_0	3.36	3.18	3.31	3.30
VC_0	163.96	261.72	258.65	342.43
Enterprise Size	371	391	350	292
$Yield_0$	76	134	140	207

Below are three scenarios tested on each state for dryland farming. Similar to the irrigated farms, Scenario 4 illustrates imperfect information and higher costs for the enhanced root trait varieties, where the only benefit falls under Category 4, providing external good in the form of carbon sequestration. Variety 1 and 2 with enhanced root traits are able to store significantly greater volumes of carbon in the soil. The farmer knows the costs, but assumes yield and weather are normal, and sees no annual benefit from increased soil carbon. Then Scenario 5 examines a possible change in yield due to drought. Scenario 6 predicts an alternative with normal weather conditions, but improved yield for the enhanced root varieties. All scenarios will be discussed together for each state.

Table 16. *Scenario 4 conditions*

<u>Scenario 4</u>: Dryland – Normal conditions, higher cost for enhanced root trait varieties	
Policy or Phenotypic Shock	
Yield	Constant
Price	Constant
Variable Cost	Increase by \$10 (i=1) and \$20 (i=2)

Table 17. *Scenario 5 conditions*

<u>Scenario 5</u>: Dryland – Drought impacting yield	
Policy or Phenotypic Shock	
Yield	Market available variety decrease by 25% (i=0) and 10% (i=1)
Price	Constant
Variable Cost	Increase by \$10 (i=1) and \$20 (i=2)

Table 18. *Scenario 6 conditions*

Scenario 6: Dryland – Normal season weather conditions, improved yield for enhanced root trait varieties	
Policy or Phenotypic Shock	
Yield	Enhanced root trait varieties increase by 10% (*i*=1) and 25% (*i*=2)
Price	Constant
Variable Cost	Increase by $10 (*i*=1) and $20 (*i*=2)

5.2.1 Colorado

Scenario 4, 5, and 6 were applied to Colorado's average dryland farm data and are presented in Table 19.

Table 19. *Results for Scenario 4, 5, and 6 in Colorado*

Colorado							
Scenario 4 **Optimal Gross Margin = $33,909.40**							
	Yield	**Level of Activity**	**Price**	**Shadow Price**	**Variable Cost**	**Allowable Increase**	**Allowable Decrease**
Variety 0	76	371	3.36	3.36	-163.96	Infinite	10
Variety 1	76	0	3.36	3.49	-173.96	10	Infinite
Variety 2	76	0	3.36	3.62	-183.96	20	Infinite
Scenario 5 **Optimal Gross Margin = $26,489.40**							
	Yield	**Level of Activity**	**Price**	**Shadow Price**	**Variable Cost**	**Allowable Increase**	**Allowable Decrease**
Variety 0	57	0	3.36	4.13	-163.96	43.48	Infinite
Variety 1	68	0	3.36	3.61	-173.96	16.88	Infinite
Variety 2	76	371	3.36	3.36	-183.96	Infinite	16.88
Scenario 6 **Optimal Gross Margin = $ 50,174.04**							
	Yield	**Level of Activity**	**Price**	**Shadow Price**	**Variable Cost**	**Allowable Increase**	**Allowable Decrease**
Variety 0	76	0	3.36	3.94	-163.96	43.84	Infinite
Variety 1	83	0	3.36	3.73	-173.96	30.32	Infinite
Variety 2	95	371	3.36	3.36	-183.96	Infinite	30.32

Scenario 4 gives the optimal gross margin, where the producer uses Variety 0 on all of their land, as expected without any other incentive the least costly variety is used. Similar to

Scenario 1 of irrigated farms, here the choice to sequester carbon is examined. The farmer will not grow the varieties that sequester greater volumes of carbon than the market available variety because they do not see direct monetary benefit. The shadow price for each variety give how much price premium would be required to switch from Variety 0. For Variety 1 and 2, the producer would need to receive $0.13 and $0.26 more for each bushel of corn, respectively. A market that supports a price premium for carbon sequestration or reduced cost of $10 and $20 will see the farmer choose these varieties.

Scenario 5, the producer knows drought will cause a 25% loss for Variety 0, the market available variety, and a 10% loss for Variety 1, the first generation of the enhanced root variety, while the most drought-tolerant, Variety 2, will maintain expected yield. The higher cost of this variety impacts gross margin by 22%, which is a loss of $7,420.00. The producer would not grow the market available variety unless variable cost decreased by $43.48. As drought impacts yield, drought tolerance becomes more valuable. The most drought tolerant variety is now worth $36.88 more than the market available variety.

Scenario 6 demonstrates normal weather conditions where the enhanced root varieties experience yield improvements, 10% increase in yield for Variety 1 and 25% increase for Variety 2. This yield improvement is very valuable, resulting in a 48% increase in gross margin of $16,264.64. The producer would continue to choose this variety until its variable cost increased to $50.32 more than the market available variety.

5.2.2 Kansas

Scenario 4, 5, and 6 were applied to Kansas' average dryland farm data and are presented in Table 20.

Table 20. *Results for Scenario 4, 5, and 6 in Kansas*

Kansas							
Scenario 4 **Optimal Gross Margin = $64,280.40**							
	Yield	**Level of Activity**	**Price**	**Shadow Price**	**Variable Cost**	**Allowable Increase**	**Allowable Decrease**
Variety 0	134	391	3.18	3.18	-261.72	Infinite	10
Variety 1	134	0	3.18	3.25	-271.72	10	Infinite
Variety 2	134	0	3.18	3.33	-281.72	20	Infinite
Scenario 5 **Optimal Gross Margin = $56,460.40**							
	Yield	**Level of Activity**	**Price**	**Shadow Price**	**Variable Cost**	**Allowable Increase**	**Allowable Decrease**
Variety 0	101	0	3.18	4.02	-261.72	84.94	Infinite
Variety 1	121	0	3.18	3.44	-271.72	31.34	Infinite
Variety 2	134	391	3.18	3.18	-281.72	Infinite	31.34
Scenario 6 **Optimal Gross Margin = $98,735.32**							
	Yield	**Level of Activity**	**Price**	**Shadow Price**	**Variable Cost**	**Allowable Increase**	**Allowable Decrease**
Variety 0	134	0	3.18	3.84	-261.72	88.12	Infinite
Variety 1	147	0	3.18	3.57	-271.72	56.78	Infinite
Variety 2	168	391	3.18	3.18	-281.72	Infinite	56.78

Overall Kansas displays similar results seen in Colorado's dryland scenarios. The product mix outcomes are consistent though the margin of price and costs are different.

A lack of any measurable incentive for the enhanced root trait varieties that sequester carbon, leaves them out of the mix, seen in Scenario 4. A price premium of $0.07 and $0.15 for Variety 1 and 2 respectively would change the product mix.

Under drought conditions in Scenario 5, the yield loss incurred for Variety 0 and 1 move them out of the product mix. The optimal yield preserved by the drought tolerance trait is worth

$51.34 more than the market available variety. Still the gross margin is reduced by 12%, a loss of $7,820.00.

Normal conditions and an increase in yield from the enhanced root trait varieties continue the trend as expected in Scenario 6. Here the 25% yield improvement is worth $76.78 to the producer.

5.2.3 Nebraska

Scenario 4, 5, and 6 were applied to Nebraska's average dryland farm data and are presented in Table 21.

***Table 21**. Results for Scenario 4, 5, and 6 in Nebraska*

<table>
<tr><th colspan="8">Nebraska</th></tr>
<tr><td colspan="8">Scenario 4
Optimal Gross Margin = $75,962.25</td></tr>
<tr><td></td><td>Yield</td><td>Level of Activity</td><td>Price</td><td>Shadow Price</td><td>Variable Cost</td><td>Allowable Increase</td><td>Allowable Decrease</td></tr>
<tr><td>Variety 0</td><td>140</td><td>371</td><td>3.31</td><td>3.31</td><td>-258.65</td><td>Infinite</td><td>10</td></tr>
<tr><td>Variety 1</td><td>140</td><td>0</td><td>3.31</td><td>3.38</td><td>-268.65</td><td>10</td><td>Infinite</td></tr>
<tr><td>Variety 2</td><td>140</td><td>0</td><td>3.31</td><td>3.45</td><td>-278.65</td><td>20</td><td>Infinite</td></tr>
<tr><td colspan="8">Scenario 5
Optimal Gross Margin = $68,542.25</td></tr>
<tr><td></td><td>Yield</td><td>Level of Activity</td><td>Price</td><td>Shadow Price</td><td>Variable Cost</td><td>Allowable Increase</td><td>Allowable Decrease</td></tr>
<tr><td>Variety 0</td><td>105</td><td>0</td><td>3.31</td><td>4.22</td><td>-258.65</td><td>95.85</td><td>Infinite</td></tr>
<tr><td>Variety 1</td><td>126</td><td>0</td><td>3.31</td><td>3.60</td><td>-268.65</td><td>36.34</td><td>Infinite</td></tr>
<tr><td>Variety 2</td><td>140</td><td>371</td><td>3.31</td><td>3.31</td><td>-278.65</td><td>Infinite</td><td>36.34</td></tr>
<tr><td colspan="8">Scenario 6
Optimal Gross Margin = $111,522.60</td></tr>
<tr><td></td><td>Yield</td><td>Level of Activity</td><td>Price</td><td>Shadow Price</td><td>Variable Cost</td><td>Allowable Increase</td><td>Allowable Decrease</td></tr>
<tr><td>Variety 0</td><td>140</td><td>0</td><td>3.31</td><td>3.99</td><td>-258.65</td><td>95.85</td><td>Infinite</td></tr>
<tr><td>Variety 1</td><td>154</td><td>0</td><td>3.31</td><td>3.70</td><td>-268.65</td><td>59.51</td><td>Infinite</td></tr>
<tr><td>Variety 2</td><td>175</td><td>371</td><td>3.31</td><td>3.31</td><td>-278.65</td><td>Infinite</td><td>59.51</td></tr>
</table>

Results from Nebraska's average dryland farm are still consistent with Colorado and Kansas. Again, the margins of cost and price are the difference.

Under normal conditions with no apparent benefit to the producer, enhanced root varieties that sequester more carbon are ignored in Scenario 4. A price premium of $0.07 and $0.14 would change the product mix and result in use of Variety 1 and 2 respectively.

The drought case of Scenario 5 results in use of the most drought tolerant variety that preserves yield at 140 bushels per acre. This yield protection is worth an increased cost of up to $56.34 more than the market available variety that will suffer a 25% yield loss in drought. Still the producer's gross margin in drought is $7,420.00, a 10% decrease from optimal conditions.

Under normal conditions with an increase in yield for the enhanced root trait varieties of Scenario 6 the producer's gross margin increases $35,560.35 or 47% more than with the market available variety. The ability to increase profit at this rate makes the traits of Variety 2 worth $79.51 more than the market available variety.

5.2.4 Iowa

Scenario 4, 5, and 6 were applied to Iowa's average dryland farm data and are presented in Table 22.

Table 22. *Results for Scenario 4, 5, and 6 in Iowa*

Iowa							
Scenario 4 **Optimal Gross Margin = $99,475.64**							
	Yield	**Level of Activity**	**Price**	**Shadow Price**	**Variable Cost**	**Allowable Increase**	**Allowable Decrease**
Variety 0	207	292	3.30	3.30	-342.43	Infinite	10
Variety 1	207	0	3.30	3.35	-352.43	10	Infinite
Variety 2	207	0	3.30	3.40	-362.43	20	Infinite
Scenario 5 **Optimal Gross Margin = $93,635.64**							
	Yield	**Level of Activity**	**Price**	**Shadow Price**	**Variable Cost**	**Allowable Increase**	**Allowable Decrease**
Variety 0	155	0	3.30	4.28	-342.43	151.60	Infinite
Variety 1	186	0	3.30	3.62	-352.43	59.30	Infinite
Variety 2	207	292	3.30	3.30	-362.43	Infinite	59.30
Scenario 6 **Optimal Gross Margin = $143,742.84**							
	Yield	**Level of Activity**	**Price**	**Shadow Price**	**Variable Cost**	**Allowable Increase**	**Allowable Decrease**
Variety 0	207	0	3.30	4.03	-342.43	151.60	Infinite
Variety 1	228	0	3.30	3.70	-352.43	92.30	Infinite
Variety 2	259	292	3.30	3.30	-362.43	Infinite	92.30

Continuing with the trend above of the other three states, results of Scenario 4 are similar for Iowa. The producer for the average 292-acre farm will choose the least costly variety when all else is equal. Carbon sequestration does not provide an incentive on its own for a farmer to choose Variety 1 or 2. A price premium of $0.05 and $0.10 for Variety 1 and 2 respectively would change the product mix.

Under drought conditions the producer continues with the expectation to choose the variety with the greatest yield preservation, Variety 2. The variety with the greatest enhanced root traits to maintain yield under suboptimal conditions is now worth $79.30 more than the market available variety. Use of this yield protected variety allows the producer to only lose $5,840.00 or 6% of the gross margin.

Normal conditions together with an increase in yield from the enhanced root trait varieties result in a 44% increase in profit of $44,267.20. The increase in profit from increased yield is worth paying up to $112.30 in variable costs for Variety 2 compared to the market available variety.

5.3 Summary of Main Trends

These results from the linear programming models can be summarized in the context of possible future scenarios. Climate change and market conditions are likely to shift, but the magnitude is ambiguous, and each state and farm face a differing situation. Table 23 summarizes the most consequential findings.

Table 23. *Summary of Results Analysis*

Trait	Impact to Adoption	Incentive Required or Market Mechanism	Benefit (Incentive Categories)
Carbon Sequestration	None	Price premium or cost rebate, conservation payment from government	Positive externalities (4)
Drought Tolerance	Allows for substitution of genetics for irrigation water, provides loss protection and yield gains	Education of benefits, yield warranty, closely monitor seed firms pricing	Private benefits (1, 2, 3) Positive externalities (4)
Soil Quality Improvement	Can allow for substitution away from fertilizer inputs, irrigation water, and improve yields	Education of benefits to land, communication tools for leased farms with non-operating owners	Private benefits (1, 2, 3) Positive externalities (4)

The choice to sequester carbon without known yield or profit incentives represents a near-future possible scenario. While the weather effects of climate change need to be mitigated through carbon sequestration, many farmers will not experience any negative effects for some years. It is not expected that the average farmer will choose varieties that are more expensive and sequester more carbon. Here the main takeaway is the need to reduce any monetary or time burden on farmers to encourage adoption.

As the US government or a carbon polluting company wants to offset their emissions, they need to carry the burden of costs. In a scenario where every sector is acting to mitigate climate change a farmer does not have the funds to change to costly varieties that sequester carbon. Many farms are already facing their own resource limitations and possibly distributional impacts from increased electricity costs. Reaching the goal of sequestering enough carbon to offset half of the transportation sector GHG emissions can only occur with immediate monetary incentives.

Drought tolerance offers substantial incentive on its own. If breeders can truly enhance drought tolerance in tandem with carbon sequestration, diffusion will happen rapidly. Then it will be up to the government or impartial third party to keep seed companies' pricing in check. States and farms with higher profit margins and larger farms can afford to go further and conduct soil testing, but that burden will be prohibitive for most farms.

The mix of drought tolerance, cost of water, and water availability result in dynamic tradeoffs. For irrigated farms, more expensive water pushes a farmer to use the most drought tolerant variety. For dryland farms dependent on weather, yield is highly variable. In a scenario possible in the later part of the century, weather will significantly impact yield. At this point farmers are likely to shift away completely from water intensive crops. As corn represents an important staple food item for much of the world, food security will be threatened.

CHAPTER 6 CONCLUSION AND POLICY IMPLICATIONS

Corn growers have the potential to offset more than half of the greenhouse gas emissions from the transportation sector through adoption of corn with enhanced root traits. Managing soils of working lands is an ideal solution both to adapt to challenges created by climate change and to mitigate the extent of climate change. Researchers funded through the Department of Energy are working to breed corn with enhanced root traits that increase drought tolerance, improve soil quality, and increase rates of soil carbon sequestration. Benefits provided by enhanced root corn could be maximized by complete diffusion into the US corn market.

Climate change is altering weather patterns that have historically determined where our food is grown, threatening global food security. Drought is predicted to become increasingly common and more severe in areas where corn is currently grown in the US. Adoption of modern sustainable agricultural technology has been slow and incompletely diffused. Previous research identified many factors that play into farmer decision making, characterizing a highly heterogeneous producer group. While some producers can make decisions to provide ecosystem services like carbon sequestration at a cost to their immediate annual profitability, many farmers face such narrow margins they are unable to switch to conservation practices.

This research uses a linear programming model to identify margins of cost and price premiums for the average farm in four western and central plains corn producing states under varying scenarios of carbon sequestration, drought tolerance, water availability, and yield. Producers will not provide carbon sequestration on its own without direct monetary incentive. Results from the gross margin optimization model pinpoint the necessary price premium to overcome increased costs. In a scenario where the producer realizes no private benefits from adopting varieties that intensify carbon sequestration and cost $20 more, a price premium of more than $0.11 per bushel of corn sold from irrigated farms in Colorado and likewise $0.08 in in Kansas and Nebraska would shift their decision.

The value of drought tolerance increases dramatically as water scarcity increases and yields are protected. Under the irrigated scenarios producer can shift away from expensive and scarce water resources, substituting for genetic input of drought tolerance.

As research continues and new varieties of corn with enhanced root traits become available, policy needs to carefully track costs and prices. The market now does not fully reward for adoption of conservation technology, and imperfect competition in the seed market is likely to take advantage of gains in yield and drought tolerance, leaving the farmer in the same economic position. Each region and farm size face different cost constraints and as such any policy needs to be flexible to encourage adoption and greatest impact to mitigate climate change.

While adjusting land management represents the most cost-effective tool to mitigate climate change, complete diffusion of enhanced root trait corn will not happen through unaided market-based mechanisms. Changing weather patterns directly impact the corn market and corn production needs to change accordingly. As climate adaptative crops become available the primary focus of policy needs to be limiting the burden on farmers. This paper identifies several key areas where policy can influence higher and faster diffusion rates.

Carbon sequestration, on its own, will not be adopted widely. Enhancements that do not provide other private benefits to the farmer are not enough incentive. The trait of drought tolerance to reduce water requirements, increase efficiency, protect yield in drought or increase yield across the distribution has the power to drive adoption. Ultimately, the greatest influence to adoption is the impact on gross margin for each farmer. In a market with over 300,000 operations, corn growers sell their grain in a market with perfect competition. In contrast, those hundreds of thousands of farmers buy their seeds from only four major suppliers with increasing market power. This discrepancy illustrates the need for policy intervention that protects their ability to gain producer surplus through adoption of corn with enhanced root traits.

Additional policy considerations are influential as well. Soil testing requirement for small farms needs to be avoided. Farms engaged with government conservation programs should be automatically offered education and monetary incentive to sequester carbon. Regions facing limited options for seeds and higher seed costs need intervention from an impartial third party to offset increased seed costs. Regions with greater options of selling grain can support mechanisms to include a price premium for carbon offsets.

Complete diffusion of climate smart corn with enhanced root traits is possible with attention in the right areas of the market. The massive magnitude and diversity of the US corn market hinders a simple direct solution yet offers an impressive opportunity to sequester significant volumes of carbon. Implementation costs are eclipsed by the benefit of avoiding the worst effects of climate change to our future global society.

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