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ECONOMIC ANALYSIS OF WESTERN CORN ROOTWORM INJURY TO CONTINUOUS CORN IN NORTHEAST NEBRASKA

by

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ECONOMIC ANALYSIS OF WESTERN CORN ROOTWORM INJURY TO CONTINUOUS CORN IN NORTHEAST NEBRASKA

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The most economically significant corn pest in the US Corn Belt is the Western Corn Rootworm (WCR), *Diabrotica virgifera virgifera* LeConte. This study compares a field experiment outcome of 4 different treatments against WCR, which consist of a rootworm Bt corn pyramid (SmartStax®) and non-rootworm Bt trait hybrid (VT2P), with or without the addition of the rootworm soil insecticide (Aztec®) to identify the risk-reward trade-off for each one of them. Observed prices were used for the years in the study (2020, 2021, and 2022), and low and high price scenarios were simulated for the period, to incorporate different dynamic relations between years. Also, different WCR Bt resistance levels and rootworm densities were accounted for: fields were classified into four groups based on susceptibility (corrected survival ≥ 0.5 and < 0.5) and population pressure (root injury for the control treatment ≥ 1 and < 1). This study also addresses how crop insurance plays a role in offsetting revenue to farmers from the fields most affected by WCR, at two insurance coverage levels: 70% coverage level – a commonly used level - and 85% coverage level - as a specific strategy with moral hazard implications. We identified that SmartStax® was the most profitable option although adding the insecticide reduces production risk exposure. Also, crop insurance gives an advantage to non-rootworm Bt traits and the 85% coverage level for fields that presented low resistance but high population pressure.

Content

1. Introduction

Corn is one of the most important crops in the United States, with the country being the world's largest producer and exporter of corn. According to the USDA, 13.7 billion bushels of corn were produced in 2022, with an average yield of 173 bushels per acre (USDA NASS - Quick Stats 2023). With the production concentrated in the Midwest, the states of Iowa, Illinois, Nebraska, and Minnesota are the top-producing ones. Nebraska, as the 3rd biggest state producer, harvested 1.4 billion bushels in 2022, with a yield of 165 bushels per acre. Most of the corn produced is for animal feed and ethanol production, with smaller amounts used for human consumption and other industrial uses (USDA NASS - Quick Stats 2023).

Corn production is a complex and dynamic system influenced by various factors such as weather conditions, pest and disease outbreaks, and changes in technology and farming practices. The insect species responsible for the greatest control costs and yield losses in the country are *Diabrotica* species, accounting for around $1 billion annually, according to Wechsler and Smith (2018). Among the five *Diabrotica* species that make up the North American corn rootworm complex, the most economically significant one for the US Corn Belt is the Western Corn Rootworm (WCR), or *D. virgifera virgifera* LeConte. The WCR feeds on the roots of corn plants, causing damage that can reduce crop yields and quality (Gray, Ratcliffe, and Rice 2009).

WCR can impact producers in two ways: it directly affects fields' yield potential by damaging corn crops and consequentially impacting profitability, and it also exposes farmers to production risks because, in the event of adverse weather conditions, yield potential is worsened. Risk exposure is also associated with the current WCR population density compromising future corn crops, given the overwintering nature of the pest. Therefore, WCR population density increases over the years for as long as corn is planted continuously in the field (the biology management of the pest is described in detail in the Literature Review).

In this study, we analyze the economic outcome of four different treatments against WCR in Northeast Nebraska. The economic outcome is based on the trade-offs between the treatment's profitability and the production risk exposure offered by each treatment, laid out in a risk-reward analysis. The risk-reward analysis offers farmers a tool to identify how much they would need to accept monetarily given a certain production risk exposure. If the trade-offs are justifiable or not will depend on how much value each farmer individually attributes to increasing profitability versus assuming a higher risk exposure. The trade-offs are built considering different production characteristics in continuous corn (fields where farmers planted corn for two or more consecutive crop seasons), such as resistance levels (susceptibility), WCR population densities, crop insurance decisions, and price scenarios. The continuous corn system history is associated with a heavy emphasis on confined livestock production in the region that requires high volumes of corn (Reinders 2021).

In the attempt to control the pest, insect management practices place selection pressure on WCR populations through the continuous use of genetically modified hybrids that express one or more proteins derived from *Bacillus thuringiensis* Berliner (WRC Bt toxins) (Reinders et al. 2022). These proteins are toxic to corn rootworms, and expression in corn plants can provide effective control by killing susceptible individuals. However, prolonged and widespread use of WCR Bt traits has led to genetic shifts that can affect the susceptibility of populations. The selection pressure allows the survival and reproduction of insects that naturally present resistant traits and that are not harmed when exposed to toxins or insecticides' modes of action. Over generations, the number of individuals resistant to the toxins increases and collectively some level of field-evolved resistance will be present in the population (St Clair et al. 2020).

The four different treatments against WCR evaluated in the present study consist of two corn hybrids, a WCR Bt hybrid (the SmartStax® pyramid), and a non-WCR Bt hybrid (VT2P), with or without the addition of the rootworm soil insecticide (Aztec®). Because the field experiment had not yet considered the economics behind these four tactics used, the objective of this study is to compare the trade-offs among treatments in the risk-reward analysis, given that fields present different resistance levels and population densities. Three corn price scenarios are considered: in the first scenario, the observed spot price for October of each year is used; in the second scenario, all years are assigned the lowest October price of the period (the low-price scenario); and in the third scenario, all years are assigned the highest October price of the period (the high-price scenario). The corn price scenarios incorporate the dynamic relationships between years, simulating what profitability would have looked like if the corn prices, an exogenous random variable, were low or high in the period, capturing the sensitivity of results to price. This study also addresses how crop insurance policy plays a role in offsetting revenue to farmers from the fields most affected by WCR, at two insurance coverage levels: 70% coverage level – a commonly used level - and 85% coverage level - as a specific strategy with moral hazard implications.

More than ever, complimentary or sequential tactics within an Integrated Pest Management (IPM) framework are needed as a strategy to avoid yield losses and resistance. It is not always clear though what input combinations are economically optimal for farmers when taking into consideration different treatment yields versus their costs and production risks. The management of WCR relies on farmers investing in more productive biotechnologies to achieve expected yields, while they need to control their costs and make decisions at a moment when corn prices and yields are unknown. The overall goal of the present study is to contribute to the literature on the economics of corn rootworm management through the lens of risk-reward to help farmers make more informed decisions, especially in fields with different resistance levels and population densities.

2. Literature Review: Western Corn Rootworm biology / management

As a univoltine coleopteran, the WCR new generation emerges from eggs during early summer in cornfields in the larval stage, the most aggressive phase of the pest, feeding on corn roots, during a time with the most rapid period of vegetative corn growth (Bryson, Wilbur, and Burkhardt 1953). The infestation level is determined by eggs surviving the overwintering period and future population density is determined by survival to the adult stage. Adults feed primarily on corn reproductive tissues and pollen and lay eggs from July through frost (Woodson and Gustin 1993). Overwintering egg mortality varies according to environmental conditions. One study has shown a general 50% mortality rate during the egg stage (Godfrey et al. 1995), and the total WCR survival rate from egg to adulthood is estimated to be 11% (Pierce and Gray 2007). Female adults typically lay eggs in existing cornfields, which leads to increases in WCR densities in continuous corn over time (Meinke et al. 2009). Because WCR has a narrow host range, hatching larvae can survive only a few days without feeding on suitable hosts, like corn plants or other grasses (Spencer et al. 2009).

Root feeding by the pest lead to interferences in water and nutrient uptake, potential plant lodging, and lower grain yield because of the reduction in plant biomass and growth (Reinders et al. 2022). The first documented feeding damage reported in Nebraska caused by WCR goes back to 1929 with more significant injuries being reported during the1940's (Tate and Bare 1946). Tinsley, Estes, and Gray (2013) estimated that for every node of root injury during the larval feeding phase, there is a 15% reduction in grain yield. The impacts of WCR on yield depend on the interaction of the population densities in the fields with corn hybrid genetics, environmental conditions, and tactics being used to manage the pest (Urias-Lopez and Meinke 2001). Crop rotation prevents WCR development because it allows a break in the cycle of host-crop production year after year, with systems that intercalate non-host crops, such as soybeans (Spencer et al. 2009).

The WCR is very adaptable to different pest management practices (Meinke, Souza, and Siegfried 2021). A rotation-resistant variant has been identified in the eastern areas of the Corn Belt, where unexpected damage to first-year corn can occur after eggs have been laid in a non-host crop in the previous year (Levine et al. 2002). This adaptation ability is potentialized in areas where two main WCR management strategies are used in continuous corn production: insecticides (both soil and foliar against larval and adult stages, respectively), and transgenic corn (Meinke et al. 2009, Meinke et al. 2021). Resistance evolution to insecticides is a consequence of multiple applications per season or continued use of a single mode of action, and resistance evolution to transgenic corn expressing insecticidal proteins is a consequence of the continuous cultivation of rootworm-active traits (Reinders et al. 2018). Pest resistance is a natural phenomenon that occurs when targeted pests are exposed to control technologies and become less susceptible to them through the natural selection of resistant individuals (Pimentel 2005). Managing resistance is a constant trade-off to extend the economic lifespan of a product: farmers want to keep pest density at a very low level by increasing the use of genetically modified seeds and protect yield within a season, but at the same time prevent resistance and preserve product effectiveness over time by reducing the selection pressure from the product (Lemarié and Marcoul 2018).

The first transgenic product against western corn rootworm was built upon the trait Cry3Bb1, developed by Monsanto, first commercialized in 2003 but widely used ever since (Crowder et al. 2005). Subsequently, the Environmental Protection Agency (2015) registered Cry34Ab1 + Cry35Ab1, launched by DuPont Pioneer in 2005, mCry3A launched by Syngenta in 2006, and eCry3.1Ab, also launched by Syngenta, in 2012 (Gassmann 2021; Environmental Protection Agency 2015). The first three transgenic corn traits expressing insecticidal Cry proteins were marketed as single-trait products by each of those companies, and all were derived from the soil bacterium *Bacillus thuringiensis* Berliner (Reinders et al. 2022). The intense usage of hybrids containing insecticidal rootworm traits, especially in regions with confined livestock production that uses corn as a feedstock in continuous systems, led to rapid WCR adaptation to Bt traits in the US Corn Belt. In 2009, field-evolved rootworm resistance was documented in

Iowa, and from 2012 on, resistance to all commercialized Bt traits occurred (Gassmann 2021).

Pyramided corn hybrids with multiple Bt traits targeting the WCR were presented as a way to mitigate the effects of single-trait resistance and delay resistance evolution (Jakka, Shrestha, and Gassmann 2016). Pyramided products containing two Bt proteins were tackled by companies through cross-licensing agreements and one of the first stacked varieties introduced in the market was SmartStax®, developed by Monsanto and Dow, back in 2007 (Dow AgroSciences 2013). Later in 2010, it embodied 8 different traits, including a gene combination of the proteins Cry3Bb1, from Monsanto, and Cry34/35Ab1, targeting the WCR from DowDuPont (Environmental Protection Agency 2015). Traits included protecting against above-ground and below-ground insects (including WCR) and broad herbicide tolerance.

A study conducted by Head et al. (2014) showed that these proteins combined (Cry3Bb1 and Cry34/35Ab1) caused at least a 99% reduction in adult corn rootworm emergence. This study was conducted in 2014, showing the efficacy of pyramided traits as a solution against resistance. However, resistance evolves rapidly over time: in 2021 already 92% of WCR populations exhibited incomplete resistance to Cry3Bb1 + Cry34/35Ab1 corn, documenting a general WCR susceptibility change since the technology was introduced (Reinders et al. 2022).

Because of persistent rootworm resistance to transgenic corn, farmers have been returning to the use of conventional insecticides as one more management tactic against this pest (Dunbar, O'Neal and Gassmann 2016). The most used insecticides against WCR are pyrethroids and organophosphates, either in soil or foliar applications (Pereira et al.

2015). Soil-applied insecticides do not necessarily reduce the larval population density or survival to adulthood, but they can protect the main root zone when WCR are present (Gray and Steffey 1998). Aztec® is an example of an organophosphate soil insecticide, previously owned by Bayer Crop Science and currently owned by AMVAC, that can be applied at planting time in-furrow as a granular product. (AMVAC 2023; Petzold-Maxwell et al. 2018; Levine and Oloumi-Sadeghi 1991). The four treatments that were chosen for this study are a combination of 2 hybrids with or without the addition of the Aztec® insecticide. One of the hybrids is the pyramid SmartStax® (Cry3Bb1 + Cry34/35Ab1) and the other one is VT2P (non-WCR Bt). Both hybrids have the same genetic background with only the presence or absence of WCR Bt traits differentiating both products.

3. Literature Review: Integrated Pest Management (IPM) in Agricultural Economics

According to one of the definitions proposed by the United Nations, Food and Agriculture Organization (1994) described in Perkins (2009) IPM integrates “several available pest control techniques that discourage pest population development” (p. 583). Perkins (2009) also emphasizes that IPM must always be accompanied by an explanation of its meaning, because of the immense variety of ideological contexts that exist surrounding the concept: it can be intended to “maximize grower profits, sometimes to reduce pesticide use and protect the environment, and sometimes to place pest control on a firm scientific foundation (biology of the pest and its populations)” (p. 584). Aiming to define IPM at a minimum, the author specifies that the “development of IPM methods of pest control will focus on the respective population dynamics of the crop plant producing biomass and the various other organisms that suppress its yields. At the same time, the economic aspects of IPM and the potential for environmental contamination by pesticides will be important for the acceptability of IPM-based practices. In addition, IPM specialists will generally not seek eradication but instead, focus on management" (p. 584).

Most of the IPM concepts in agricultural economics have focused over the past 40 years on decisions using the Economic Injury Level (EIL) and Economic Thresholds (ET), tactical decision rules that associate the current level of infestation to its economic loss, comparing the anticipated damage to the costs of control (Pedigo, Hutchins, and Higley 1986). These concepts were proposed by Stern et al. (1959) who, when acknowledging the problem of extensive insecticide use, developed a standard way to determine whether or not a crop should be treated against a certain pest. According to the author, treatment should occur when the damage caused by uncontrolled populations exceeds the costs of controlling them, balancing production risks with financial risks. The EIL-based decision assumes that, if a field is not treated when the pest population indicates the field should be treated, then the pest population only increases, and the loss in crop yields is continuously greater than the costs of the injury level. What this management tool does not account for is that different outcomes are possible based on different probabilities and events. Pathogenic outbreaks, unanticipated favorable growing conditions, and many other examples can cause two types of errors in interpreting the moment when the pest population is identified: either it is below EIL when actually the field should be treated within the next days, or it is above EIL, so the field is treated, when in fact, pest population would have decreased without targeted interference (Mitchell and Hutchison 2009).

Another issue of the EIL-based decision is that it represents a mean calculated based on 5 different parameters (cost of the pest control treatment, projected crop value, crop injury per pest, yield loss per unit of crop injury, and efficiency of the pest control treatment) when, in reality, those 5 paraments can assume multiple values and vary across different moments, leading the means to also vary (Pedigo, Hutchins, and Higley 1986; Ragsdale et al. 2007). Onstad, Bueno, and Favetti (2019) described how Onstad (1987) extended the ideas developed in the ’50s and that had been improved in the ’70s, incorporating the time during which the pest can possibly occur in a more dynamic way, which means sampling and control tactics would not be restricted to a given period and should be performed when the population is increasing as well as decreasing. By developing both linear and quadratic density-damage functions, Onstad (1987) was able to capture the infestation levels that change throughout a season and defined control as time-dependent management of a pest population.

Over the past decades, many discussions and improvements have been made in the EIL and ET methodologies, but even the most sophisticated ones offer a “treat/no-treat” decision for immediate use in response to field populations (*ex-post)*. A more strategic long-term analysis where decisions are made in advance of an upcoming season (*ex-ante*) started to gain evidence in the early 2000s motivated by the cost of sampling and new transgenic technologies being introduced in the market, specifically for WCR (Crowder, Onstad, and Gray 2006). An *ex-ante* approach does not ignore the importance and how foundational EIL has been for successful IPM programs, but it considers EIL to be one of several important tools present in a more dynamic assessment that incorporates economic performance, risks, and information to evaluate the value of IPM in advance of a growing season (Mitchell and Hutchison 2009).

An economic analysis of different IPM practices or treatments usually accounts not only for how production-efficient each treatment is but also takes into consideration its profitability (net returns). *Ex-ante* approaches allowed economists to focus on pest-damage functions to estimate the economic impact of the WCR under different *ex-ante* treatment scenarios or the value of new control technologies, whose implementation occurs during planting time. Those functions link the biological system with the economic system, where yield losses are a function of population density or pest damage (O'Neal et al. 2001; Mitchell, Gray, and Steffey 2004).

Alston et al. (2002), for example, using pest damage function, estimated that the benefit to farmers adopting the rootworm-resistant transgenic corn in the year 2020 would have been $460 million if adopted on all the acres treated for WCR in the United States. Mitchell et al. (2004) and Yang et al. (2007) both focused on developing WCR damage functions using field experimental data that could be used to estimate economic losses due to WCR. Mitchell et al. (2004) described a composed-error model, as opposed to conventional regression models, to estimate the pest-damage functions while Yang et al. (2007) focused on the net benefit of soil insecticide and Bt corn and found that soil insecticide generates a net loss ranging about $0.50-$3.25/acre, while Bt corn generates a net benefit ranging $2.50-$7.00/acre. Both studies looked at the WCR soybean rotation variant. MacLeod (2007) conducted a cost-benefit analysis using a stochastic model on WCR and showed that strict implementation of control measures can be more costly than the damage likely to be caused by the pest when the cost resulting from forced rotation is accounted for in the United Kingdom.

Dun, Mitchell, and Agosti (2010), explain that data field plots or observations, such as data from field trials of new pest control technologies, are a common source for estimating pest damage functions and that the panel data – data from various groups through time - is commonly nested (pooled). The idea is that data can be pooled by more than one index (year, location, and treatment). Also, these panel data are often unbalanced – locations and treatments change over the experimental or sampling period so the number of observations or replicates by location and treatment changes. These concepts are important to the present study because although we will not be calculating pest-damage functions, we use an unbalanced panel dataset in an *ex-ante* field experiment context to obtain a risk-reward analysis.

Risk is also essential to account for to fully understand the impact of different pest management strategies (Cuperus and Berberet 1994). According to Olson (2004), there are a few types of risks farmers need to deal with in agricultural systems: production, financial, marketing, legal, environmental, and human risks. On the production risk side, WCR management can impact farmers' net returns depending on the intensity in which the corn fields are affected by the pest. WCR pest-damage functions allow for net return impact inference by inputting root injury to estimate yield losses, as shown by Dun, Mitchell, and Agosti (2010).

Hurley, Mitchell, and Rice (2004) analyze corn production risk by comparing the actual return with a potential return per acre, using *ex-ante* control methods in different population densities in Nebraska. Although their study focuses on a lepidopterous insect pest, the idea of risk applies. The authors wanted to conceptually model how risk influences the value of Bt biotechnology under different biotechnology price scenarios and how it impacts farmers' welfare. The paper explains that the welfare benefit of Bt corn to farmers is part of the US Environmental Protection Agency (EPA)'s risk assessment. According to the authors, even though the literature continues to debate the relationship between pest control and risk, many farm consultants, extension educators, and researchers suggest Bt corn can be used to reduce production risk.

Milne et al. (2015) emphasize that how farmers perceive risks, rather than farmers' actual losses, plays an important role in pest management: "If farmers underestimate the risk of infestation and grow conventional corn then the pest will flourish and diminish yields. If, however, farmers exaggerate the risk and plant too much Bt corn, then there is an increased risk that the pest will adapt to its new host and threaten the long-term production of corn" (p. 2). In the case of WCR, because it overwinters, carry-over effects (adult production and egg laying in the following season) of continuous corn help develop farmers' perception of the production risk they are exposed to. Liu and Chen (2021) explain that risk exposure is the propensity or predisposition to be adversely affected. This perceived threat influences farmers' decisions on pest management and can create coordinated responses from farmers that are often influenced by similar circumstances (Milne et al. 2015).

There is a vast literature that has examined the effect of genetically modified crops on production risks, such as their impact on yield variability and distribution (Shi, Chavas, and Lauer 2013; Chavas and Shi 2015; Sanglestsawai et al. 2017). To evaluate the effect of Bt traits on production risk, Lakhani et al. (2013) measured the cost of risk, that is, the number of bushels of corn per acre a farmer is willing to give up to replace a risky yield with mean yield, which depends on the farmer’s degree of risk aversion. Also, risk exposure can be measured in multiple different ways according to the purpose of each study. Goodwin and Piggott (2020) for example, measure risk by the rate of indemnities paid per unit insured when using crop insurance to analyze farmers’ claims on yield sensitivity to weather stress.

A study that focused on risk exposure generated by WCR was proposed by Aglasan, Goodwin, and Rejesus (2021). They examined the production risk effect of Bt corn with rootworm-resistant traits and concluded that WCR Bt biotechnology has reduced corn production risk. They also stated that this type of information is useful when there are concerns about moral hazard in the crop insurance program. Moral hazard occurs when an insured party alters their behavior in a way that increases the likelihood of a loss, knowing that they are protected by insurance. In other words, insurance causes insured parties to behave more recklessly because they are protected from loss. Just, Calvin, and Quiggin (1999) state that farmers that tend to purchase crop insurance are the ones that have higher-than-premiums expected indemnities. Farms with lower expected indemnities are priced out of the program (they are not willing to pay high premiums).

Some studies have focused on the economic analysis of WCR injury using field experimental data in the US Midwest, but they are mainly focused on establishing economic thresholds or measuring the root injury difference from Bt corn to non-Bt corn. Dunbar and Gassmann (2013) for example, evaluated crop rotation in cornfields and observed the presence of resistant WCR (measured by the occurrence of this insect in soybean fields) but concluded that the occurrence was below the economic threshold, suggesting crop rotation was a viable pest management strategy. St Clair, Head, and Gassmann (2020) sampled four to eight fields in 2015, 2016, and 2017 that had reported more than one node injury from WCR. Their main conclusion was that farmers derived an economic benefit from planting Bt corn to manage WCR. Gyeraj et al. (2021) also conducted a 3-year study, in their case to determine WCR feeding damage in sweet corn. They found that a WCR density of up to 8 adults per ear is not likely to lead to economic damage in sweet corn. To our knowledge, this study is the first one to use field-level experimental data to evaluate WCR's impact on yield to analyze profitability and production risk exposure on a commercial level from a farmer's perspective, incorporating moral hazard implications.

4. Methods

The following subsections offer a detailed explanation of 1) the field experiment, 2) how UNL's budgets are used to calculate costs, revenue, and profits, 3) how risk is defined for this study, 4) how the profitability-risk analysis is designed, and 5) how crop insurance works and what are the coverage levels chosen.

4.1.WCR Field Experiment

The WCR field experimental research was performed in the years 2019, 2020, 2021, and 2022 by Lance J. Meinke, Jordan D. Reinders, and Timothy B. Dang who were responsible for organizing, implementing, conducting, monitoring, and analyzing the results of the experiments in northeast Nebraska in the years mentioned.[1] Fields were numbered for identification purposes, located in Pierce, Stanton, Cuming, Boone, Platte, Colfax, Dodge, and Saunders counties, as shown in Figure 1). There were 10 fields in

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[1] Detailed description of Field Experiments can be found in Reinders (2021).

2020 (fields number 2,3,6,7,8,10,12,15, and 16), 11 fields in 2021 (2,3,6,7,8,9,10,12,15,16, and 17), and 10 fields in 2022 (2,3,7,8,9,10,15,16, 18, and 19) as shown in Table 1. Fields were chosen considering their high risk for significant plant injury from corn rootworms based on the historical use of SmartStax® (Cry34Ab1 + Cry35Ab1) in a continuous corn environment for at least 2 years. For each field, using Bt bioassays, susceptibility to SmartStax® was determined, which would indicate the WCR Bt resistance level in each field. To do that, gravid females were collected the previous year and brought to the laboratories at UNL, eggs were obtained and held through an obligatory diapause period for 5 months. The eggs hatched out in the following season and the neonate progeny of the F1 generation from each population were obtained following the methodology described in Wangila et al. (2015) and used in bioassays following the methodology described in Gassmann et al. (2011). Twelve neonate F1 larvae were infested onto the roots of each of 12 replicated SmartStax® and isoline (non-WCR Bt) plants. Larval survivors were collected and corrected survival for each population on SmartStax® was calculated as the complement of corrected mortality using Abbott's correction (Abbott, 1925).

The fields were classified as those with corrected survival equal or higher than 0.5 (higher resistance levels, hereafter high) and those with corrected survival lower than 0.5 (lower and moderate resistance levels, hereafter low). Next, in a partnership between researchers and farmers, the experimental corn plots were placed in the same areas adult collections had been made previously and where susceptibility was determined. Each field consisted of 4 plots, and each plot was designated to a different treatment, making up a total of 4 treatments. Each plot was 4-row x ca. 200 ft long (10.2 ft x 200 ft). For planting, seeds were treated with clothianidin at 0.5 mg/seed – a cost incorporated in the seeds' price. Aztec® soil insecticide was applied at planting in the seed furrow. The four treatments were:

1) "VT" - Non-rootworm trait hybrid (VT2P);
2) "VT + A" - Non-rootworm trait hybrid (VT2P) + Aztec® 4.67G @ 3 oz/1000 ft (85 gm/305 m);
3) "SS" - Cry3Bb1 + Cry34/35Ab1 hybrid (SmartStax®);
4) "SS + A" - Cry3Bb1 + Cry34/35Ab1 hybrid (SmartStax®) + Aztec® 4.67G @ 3 oz/1000 ft (85 gm/305 m).

Those treatments were chosen because they assess the Integrated Pest Management and Insect Resistance Management framework of commonly used WCR management tactics. Also, treatments would allow us to measure yield loss derived exclusively from root-feeding corn rootworms, since both seeds - SmartStax® and VT2P - were from the same genetic family and both included Bt traits that kill ear- or foliage-feeding Lepidopteran pests, such as European Corn Borer, *Ostrinia nubilalis* (*Hübner*), with the difference that the pyramid SmartStax® expresses rootworm-Bt proteins derived from *Bacillus thuringiensis* Berliner that kill rootworm larvae (although not adults). As VT2P did not express rootworm-Bt traits nor was protected from rootworm injury, it was included as a control. The addition of the Aztec® soil insecticide to SmartStax® can be redundant, as both have activity against WCR. However, when the Aztec® is included with VT2P, the insecticide represents the only method of control against WCR.

During the growing season, 10 plants per treatment strip were dug to analyze the proportion of root damage. Roots were rated for level of root injury to obtain mean root damage (RDR) per field. The RDR was measured following the injury scale developed by Oleson et al. (2005), to accurately quantify and score WCR larval injury based on the proportion of nodal roots that contained feeding injury. The scale ranges from 0 to 3, with 0 indicating no injury (no feeding damage) and 3 indicating extensive root damage (three or more complete nodes pruned). Important to note that the WCR population that caused RDR belongs to the same generation as the F1 larvae used in the bioassays to obtain corrected survival. At the end of the season, corn ears were hand-harvested at approximately 10% moisture and yield was calculated at 15.5% moisture. The two variables evaluated were:

1) RDR: root damage (0-3 node injury score Oleson et al. 2005);
2) Crop yield.

The RDR was also used to obtain rootworm pressure (relative population density) of each field: if RDR for the plot where VT2P was planted (the control treatment with no activity against WCR) was equal or greater than one (moderate-high RDR), then the entire field (the 4 plots) was classified as high rootworm pressure. In contrast, if the RDR was lower than one for VT2P, then the field and its 4 treatments were classified as being of low rootworm pressure. Important to note that within the same field, the RDR means vary depending on the plot's treatment, which means that not necessarily the plot's RDR means will correspond to the group's RDR mean this plot was classified as. By combining the results on rootworm pressure with resistance levels (measured through susceptibility bioassays), all fields were classified into 4 resistance groups:

1) Group 1 (HIGH/HIGH): corrected survival ≥0.5 (high resistance) and RDR≥1 (high rootworm pressure/density)

2) Group 2 (HIGH/LOW): corrected survival ≥0.5 (high resistance) and RDR<1 (low rootworm pressure/density)
3) Group 3 (LOW/HIGH): corrected survival <0.5 (low resistance) and RDR≥1 (high rootworm pressure/density)
4) Group 4 (LOW/LOW): corrected survival <0.5 (low resistance) and RDR<1 (low rootworm pressure/density)

4.2. Profitability: Costs and Revenue

The economic analysis is conducted by calculating what would be the real costs per acre if a farmer used the treatments on a commercial level. We assume all field operations and input costs are the same across fields except for the treatment costs and variable costs (costs that depend on productivity). Given the same market conditions, the profitability by year would vary across treatments only due to the difference in treatments' input costs and production outcomes (yields), as all other factors are held constant.

We calculate the costs per acre of a commercial field given the standard "best practices" for Northeast Nebraska in a no-tilling continuous corn rotation system using diesel pivot irrigation. Best practices are obtained from UNL corn budgets developed by Extension Specialists within the Institute of Agriculture and Natural Resources. The budget projections for each year are created using "cropping practice norms for many producers in Nebraska" and specific adjustments made to meet the needs of the current study are validated by Robert Klein, Senior Editor, and Crop Specialist; Glennis McClure, Extension Educator in Agricultural Economics; and Robert Wright, Extension

Entomologist.[2] The Nebraska Crop Budget offers a standard guideline for continuous corn, no-till, with diesel pivot irrigation. The budgets are available on the Nebraska Cropwatch website for 2020, 2021, and 2022.

The budgets are built in a way that all costs are calculated in dollars per acre and the total cost per acre is given from the summation of the field operation, materials (inputs), interest on operations capital, taxes, overhead costs, real estate costs, and ownership cost per acre. Field operations are: 1) spray spring burndown herbicide, 2) herbicide application before planting, 3) planting with in-furrow fertilizer and Aztec® application (if applicable), 4) herbicide application, 5) post-emergence herbicide application, 6) fungicide application 7) diesel irrigation and fertigation, 8) scouting, 19) grain drying, 10) harvesting, and 11) cart and hauling.[3] Each one of those operations has corresponding labor, fuel, and repairs costs for each year, as well as their specific material costs associated with application rates and percentage acre applications.

Apart from seed chosen and the use of insecticide (the treatment inputs), all the other field operations, materials, and services mentioned above are extracted from the original Nebraska Crop Budgets. No other insecticide is used, except for Aztec® - in applicable treatments. The decision to exclude other insecticides that a farmer could potentially use in a commercial field is because many different active ingredients can affect WCR which would create noise in our economic analysis when comparing costs to the real damage and outcomes obtained from the treatments.

Field production costs are classified as Fixed Costs (FC) or Variable Costs (VC). FC are the ones replicable among fields that are unrelated to treatments or yields.

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[2] Emails exchanged throughout October 2023 with two online calls on October 11th and 24th.

[3] See Appendix for full explication on field operations.

Therefore, FC per acre for a given year is the same across plots, given all were subjected to the same field operations and inputs. VC are yield-related, so VC per acre is not the same across plots as it depends on the yield per acre of each plot as well as on the treatment of each plot. In other words, the inputs associated with the treatments (seeds and/or insecticide) are considered variable costs, and the field operations and materials costs, which are calculated as a function of yields, are also considered variable costs (cart, hauling, and drying). All the other field operations and materials are FC. For FC there is an additional cost, besides field operations: crop insurance.[4] In our study, we evaluate how crop insurance can play a role in influencing farmers' decision-making. Crop insurance cost is known as a premium, which is the price farmers pay per acre to be insured and therefore, protected from potential yield losses. Premiums change according to the coverage level farmers choose (level of protection).

Besides VC and FC, we also calculate the Interest on Operations Capital, Overhead, and Taxes (IOT) associated with Total Costs (TC). Important to mention that we are focusing our analysis on the total cost of production, which means we are also incorporating the Real Estate (RE) costs and the Ownership costs associated with field operations when machinery is owned by the farmer. Real Estate costs can either represent an Opportunity Cost (in the case of landowners) or an Operational Cost (for farmers renting the land). Nebraska Crop Budgets bring the price of the land as an average of all irrigated areas of the state. Calculating the profitability using the total cost of production – which incorporates Ownership and RE opportunity - gives us the economic profit/loss of a field.

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[4] Crop Insurance will be described in detail in subsection 4.5.

On the revenue side, we assume all fields have the same marketing strategies (selling spot in the harvest month – October) and the same harvest corn price applies for all fields in a certain year. Profitability is given as the difference between revenue and total economic costs per acre, as shown in Equation 1. Because yield is a random variable, this study evaluates farmers' profitability in $/acre: how much value they can extract from one acre. In the next paragraphs, a description of field operations, cost, and price methods is offered.

$$Profit\left(\frac{\$}{acre}\right) = Harvest\ Price * Actual\ Yields - Total\ Economic\ Costs \quad (1)$$

Corn price is an exogenous variable, which is why we simulate high and low-price scenarios to incorporate different price dynamics between years. Also, by pooling yearly results, it is possible to eliminate price exogenous variation. The low price is assigned as the lowest price of the period and the high price is assigned as the highest price of the period. By doing that, we can expand the results from "as is" (actual) to "what if" (simulated) price scenarios, and see if the outcome is impacted, assuming prices are unknown by farmers.

4.3. Risk definition

We analyze treatments that have different profitability and risk exposures associated with them. WCR management can impact net returns in the intensity at which the corn fields are being harmed by the pest, so much so that root injury is one of the main variables when pest-damage functions are built to estimate yield and economic outcome (Dun, Mitchell, and Agosti 2010). The greater the root damage, the greater the likelihood of yield loss. Therefore, root damage is a measure of risk exposure for the WCR risk-reward analysis. The root (or node) injury was measured in the experiments following the scale of Oleson et al. (2005) from 0 to 3. By using the root damage scale, we can see how much each treatment allows rootworms to manifest (intensity of root feeding by WCR), indicating the production risk corn fields are exposed to under each one of the four treatments.

Important to note that the root damage is a consequence of the WCR population of the previous year, as it is caused by the progeny of the adults that emerged the year before. It can also affect what the grower might be up against the following year – so it affects the farmer's perception of how risky his/her production environment is. If a high adult population emerges from that injury, the eggs that are going to be laid will hatch in the following year after overwintering. In general, root damage represents the general density of larvae in the field relative to the previous year's infestation and the subsequent overwintering egg survival rate. Except when the larval population is very large, food becomes limiting so some mortality can occur which reduces survival to the adult stage. Therefore, production risk exposure (yield loss potential) generally depends on RDR. Ultimately, yields are a function of three things: WCR impacts, farm practices, and unobservable variables, as shown in Equation 2. Even knowing that the experiment was built around allowing the fields to only express the WCR impact, unobservable variables (related to weather or environmental conditions) could have impacted production outcomes, although we are not able to measure them. What we can measure is WCR production risk exposure, better translated through root damage.

$$Yield = f\ (WCR;\ Farm\ practices;\ Unobservable\ variables) \qquad (2)$$

4.4. Risks-vs-reward analysis description

Trade-offs are calculated in the risk-reward analysis. The reward is profitability, and the risk exposure is the treatment's RDR. Results are shown in a graph where Y-axis is the profitability in \$/acre and the X-axis is the RDR in the 0-3 node injury scale (as shown in Figures 6 through 22 described in the Results and Discussion section). The analysis is performed yearly - to reflect individual year effects - as well as pooled (nested) - to reflect the dynamic between years, following the methodology used by Dun, Mitchell, and Agosti (2010). We are interested in comparing the treatments to understand how many dollars per acre would need to be given up to have risk exposure reduced. The preferable treatment would depend on how much farmers would be willing to give up to have a risk exposure reduction. Also, we want to see how this trade-off dynamic looks like when crop insurance scenarios take place for different field conditions, considering resistance level and population pressure.

4.5. Crop Insurance

Crop Insurance is a mechanism that allows farmers to protect themselves against production risk. The US federal crop insurance is a major farm policy aimed at providing risk protection to agricultural producers, who can purchase a crop insurance contract at the beginning of the crop year. The greater the risk protection provided by a crop insurance contract, the greater the premium associated with the procurement of the contract (Mavroutsikos, Giannakas, and Walters 2021). There are multiple insurance policies with different levels of risk coverage available to producers, offered at standard percentages in increments of 5%, from 50% coverage level to 85% coverage level (Congressional Research Service, 2023).

We are interested in seeing if the fields in the study would have had their indemnity payment triggered under different coverage level policies. Indemnities bring extra revenue to make up for yield losses and might affect farmers' perception of best treatment options (when trade-offs are analyzed in the risk-reward space). We analyzed 3 different crop insurance scenarios: 1) no insurance, 2) 70% coverage level - 30% deductible, and 3) 85% coverage level - 15% deductible. For the last two scenarios, premiums are added as costs in dollars per acre. The 70% coverage level is chosen because it is the most widely purchased in the United States and as 87% of all corn acreage is insured in the country, we set the 70% coverage level as the standard (baseline) scenario (Zulauf et al. 2023; USDA 2018). The 85% scenario is chosen for two reasons: we are interested in seeing how the extreme scenario would affect outcomes compared to the standard scenario, and foremost because this scenario would have moral hazard implications, which assumes farmers would be willing to pay high premiums because they expect to receive indemnities (Just, Calvin, and Quiggin 1999). Both scenarios were compared to the no insurance scenario. Each scenario assumes all fields engage in the same coverage level over the 3 years. Actual yields were then compared to the corresponding county's Average Production History (APH), calculated as a 10-year yield average of irrigated land in Nebraska.

The Crop Insurance policy used in the study is Revenue Protection, where farmers protect their revenue based on the projected revenue. The projected revenue is calculated by multiplying the APH times the coverage level times the projected price. The projected price is the greatest value between the monthly average new-crop futures prices for corn in February (December futures contract) and the monthly average price in October (harvest time). In our study, October prices are higher for all years, which means indemnities are triggered by yields. If the actual revenue (actual yield*selling price) falls below the projected revenue (APH*coverage level*projected price) the difference makes farmers' indemnities (Groskopf and Walters 2021).

The policy and premiums used are for Enterprise Units. Enterprise Units are used in situations where all insurable acreage is for the same insured crop in the county in which farmers have a share on the date that the coverage begins for that crop year, which is the situation that fits the present study. Additionally, Enterprise Units cover acreage that follows the same methods of irrigation practice and cropping system (USDA 2021). Enterprise Units have the highest subsidy provided by Federal Crop Insurance Corporation (FCIC) than any other crop insurance policy. For the 50% through 70% coverage levels, subsidies are flat with an 80% premium subsidy (compared to 67% for the other units). For the 85% coverage level, the premium subsidy drops to 53% (USDA 2021).

5. Data

The next subsections will cover how the data for this study are obtained. Field data come from the field experiments and all the other data are open-source data.

5.1. Field Data

Fields are numbered for identification purposes and the fields' respective counties are shown in Figure 1. Table 1 presents which fields are used in each one of the years of the study. Field number 7 in the year 2020 presents data issues for treatments 1 and 3 (treatments strips were inadvertently placed outside the irrigation which led to lower yields, so they were eliminated from the dataset). Therefore, out of 124 plots, only 122 are valid and used in the analysis. A dataset is created with each plot's average criteria result, which means the data of the experiment are laid out in a matrix of 122 rows per 7 columns, each column containing: field number, county, year, treatment, group, RDR, and actual yield.

5.2. Costs

The yield obtained in each plot is an input for the budget calculator to obtain the total cost of production (total economic cost) of that respective plot. As described in the methods section, budgets are representative of the field experiment conditions applied to one commercial acre. The output of the budgets is the total cost of production per acre including treatment costs, VC, FC, and other costs (which is a sum of IOT costs and RE costs). A complete description of how costs are calculated can be found in the Appendix. Figure 2 shows the composition of each one of those costs and what they represent relative to total production costs. Treatment costs represent 16% of the total cost of production. It is in that portion that we will allow costs to vary, to measure differences among treatments. VC represents 5%, FC represents 44%, and IOT +RE + Ownership represents 36%. Figure 3 shows how the treatment's input prices change over the years in \$/acre: there is a \$6 increase in the cost of SmartStax® from 2020 to 2021 and a \$5 increase from 2021 to 2022. For VT2P this increase is \$4 in both years. Aztec® price is \$25/acre for 2020 and 2021, and \$26/acre for 2022.

5.3.Prices

To calculate revenue, the corn price series used is the monthly average spot price in October (harvest time) of each year. For the actual price scenario, we use the actual harvest prices for each year. For the low-price scenario, we attribute the lowest price of the period to all years (2020 price – $3.99/bu), and for the high-price scenario, we attribute the highest price of the period to all years (2022 price - $6.86/bu), as shown in Table 2.

For crop insurance, guaranteed revenue and indemnities are also calculated using the same price series described above. According to the Revenue Policy, the price series that should be used is the higher price between the monthly average spot price in October and the monthly average new-crop futures prices for corn in February for the December futures contract (projected price). Because the first was higher than the latter in all years, we do not make use of the projected price, as can be also seen in Table 2. Prices are obtained from the Price Discovery website (2023)

5.4. APH and Premiums

APH is obtained from the Risk Management Agency (RMA) from the United States Department of Agriculture (USDA) in their Information Reporting System which contains the Area Plan Historical Yields application that provide year average yields per county (USDA - RMA, 2023). Premiums for the Enterprise Unit, both for a 70% and 85% Coverage Level, are obtained from the same source. Table 3 presents premiums paid by farmers each year (government subsidies already included).

6. Results and Discussion

SmartStax® is the most profitable option when results are pooled across years, as shown in Figure 4. Not only fields under this treatment produce more bushels, but the higher cost of the seed justified the investment. This result means that even in a continuous corn system where fields present levels of rootworm resistance, the SmartStax® hybrid offers great control with the best profitability for farmers. For the yearly results, SmartStax® is also the most profitable option in all 3 years (Figure 5), but because of the price and yield variation, yearly profits vary: $3/acre in 2020, $376/acre in 2021, and $513/acre in 2022, with yields being 204, 215, and 212 bushels respectively. SmartStax® yields are the highest in 2020 and 2021 and in 2022, the addition of Aztec® delivers only 2 extra bushels. In 2020 and 2021, the insecticide added to SmartStax® represents a yield and a profit-reducing factor: this addition deducts 5 bushels and 6 bushels per acre respectively when compared to the seed by itself, which leads SmartStax® + Aztec® to have the worst profitability in the second year and to be close to VT2P in the first year. The insecticide does not bring monetary value to SmartStax® and in years of low corn prices, like 2020, SmartStax® + Aztec® even presents negative profitability, just like the control treatment VT2P (-$42/acre and -$44/acre, respectively). VT2P is very exposed to rootworm damage and its low yields – relative to the other treatments – do not bring the revenue needed to overcome costs in 2020. In 2021 and 2022, it has the second worst and the worst profitability, respectively.

As for adding the insecticide to VT2P, Aztec® comes as a yield and profit-increasing factor. This result is expected because in this treatment Aztec® includes ingredients that are active against WCR, which is not the case for the seed. The productivity gains are large enough to put this treatment at the second-best profitability position, but still not at the SmartStax® 's level. This result means that although Aztec® brings an improvement in profitability for the VT2P seed, it is not as high as the benefits that the rootworm-Bt pyramid can offer.

The results play a new dynamic through the risk-reward analysis when trade-offs arise. By definition, risk exposure is represented by RDR, which can assume unit-free values from 0 (minimum risk exposure) to 3 (maximum risk exposure). The risk-reward focuses on pooled results, because by incorporating the price dynamic between years, it also incorporates the rootworm carry-over (adult production and egg laying) effect over the 3 years, and it allows all same-treatment plots to be aggregated (nested).

As shown in Figure 6, VT2P, as the control treatment, naturally presents the highest risk exposure, with an RDR mean of 1.37, which reflects what the root damage looks like if WCR is not targeted. Adding Aztec® to VT2P reduces the RDR mean to 0.73 (46.7% less). Although risk exposure decreases, using the rootworm-Bt pyramid (SmartStax®) decreases RDR mean even more, reaching 0.34 (53.4% less compared to VT2P + Aztec®). So far, the study suggests that the yield increase provided by SmartStax® is due to the reduction in root damage, which allows the corn to develop better. In turn, SmartStax® + Aztec® presents the least risk exposure of all treatments (RDR mean of 0.20 - a 41.4% reduction relative to SmartStax® alone), but it is also accompanied by a reduction in yield and profit.

In general, irrigated corn yield may only be minimally impacted by rootworm injury when RDR is less than 0.5, however, we still need to contemplate the downside represented by any level of risk exposure: there are variables (like weather and environmental conditions) that we are not able to observe that impact yields in unknown ways. When risk exposure decreases, the downside is gradually eliminated, and when risk exposure increases, the downside continuously increases. If farms are hit by a thunderstorm, for example, how treatments are going to be affected will depend on how they are exposed to production risk. Therefore, farmers that seek to reduce risk exposure will value having lower RDR, as opposed to farmers that are profit-seekers that will prefer to face some risk exposure to seek higher profitability. This is especially true for plant lodging, which is greatly reduced when Aztec® is added to SmartStax® or VT2P. Plant lodging is a result of unobserved variables such as bad weather events, and farmers who had a history of it in commercial fields will likely be more willing to pay for the insecticide costs. In our study, because corn was hand-harvested, the yield loss resulting from plant lodging is not incorporated. But in a commercial field that uses mechanical harvest, the combine is not able to pick up corn ears from lodged plants.

Two trade-offs can be identified in Figure 6. The first one is between SmartStax® and SmartStax® + Aztec®. As mentioned, adding the insecticide reduces RDR mean by 41.1%, but profitability decreases by $36/acre. Because in absolute terms risk exposure only decreases by 0.14, and because both treatments that use rootworm-Bt traits already have low-risk exposure, only farmers that are concerned about production risk exposure would prefer to add the insecticide. The second trade-off is between the two treatments that use the insecticide. Switching from VT2P + Aztec® to SmartStax® + Aztec®, only reduces profit by $11/acre, while RDR mean is reduced by 0.53 (72.6% reduction).

The risk-reward trade-off changes when crop insurance is incorporated. Figure 7 shows the risk-reward pooled results for 70% and 85% coverage levels and the profit changes by each treatment. In our analysis, 7% of all 122 plots would get indemnities using the 70% Coverage Level (CL), and 30% using the 85% CL. For the 70% CL, there was a total of 8 sites that got indemnities, as shown in Table 4: 4 VT2P plots (one in 2020, one in 2021, and two in 2022), 3 VT2P + Aztec® plots (one in 2021, and two in 2022), no plots for SmartStax® treatment, and one plot for SmartStax® + Aztec®

treatment in 2022. Those sites are fields numbered 6, 10, and 15 (Boone and Saunders counties). For the 85% CL, there is a total of 26 sites that get indemnities, also shown in Table 4: 11 plots for VT2P (three in 2020, five in 2021, and three in 2022), five sites for VT2P + Aztec® (two in 2020, one in 2021, and two in 2022), five plots for SmartStax® (one in 2020, two in 2021, and two in 2022), and five plots for SmartStax® + Aztec® (one in 2020, two in 2021, and two in 2022). The same eight sites in the 70% CL are repeated in the 85% CL, which means eighteen more sites are added: they belong to fields numbered 6, 8,10, 12, 15,16, and 18 (Boone, Cuming, Colfax, Saunders, and Stanton counties). Fields 17 (Colfax), 7 and 9 (Cuming), 13 (Dodge), 3 (Pierce), and 19 (Stanton) do not get indemnities at all. All fields in Boone and Saunders get indemnities in all 3 years – this result can suggest unobservable variables affected yields in these two counties.

Important to note that the number of sites that get indemnities in the two different coverage levels is not enough to change profit averages for pooled results to a point where other treatments would surpass SmartStax®'s profitability. But indemnities do change the profitability ranking of treatments, affecting the trade-offs. The 70% CL brings $11/acre to VT2P + Aztec® and $21/acre to VT2P, while SmartStax® and SmartStax® + Aztec® lose $4/acre (premiums represent costs as they are higher than indemnities). As a standard crop insurance scenario, the 70% CL is likely to be the most realistic profitability scenario farmers would face. In this case, not only trade-offs are affected, but also one more trade-off is identified: VT2P becomes more profitable than SmartStax® + Aztec® ($266/acre versus $257/acre, respectively) which means farmers would face the choice of giving up $9/acre to have mean RDR reduced by 1.17. When we compare VT2P + Aztec® to SmartStax® + Aztec® the decision-making process is also affected: if with no insurance farmers would have to accept losing $11/acre to reduce mean RDR by 0.53, now they would have to accept a $26/acre loss. Looking exclusively at the 7% of fields that receive indemnities, because they naturally performed worse than the average, the profit increase provided by crop insurance is noteworthy: +$17/acre for SmartStax® + Aztec®, +$133/acre for VT2P + Aztec® and +$175/acre for VT2P.

For the 85% CL, as even more VT2P treatment plots receive indemnities, this treatment gets even closer to what the addition of the insecticide provides, with a difference of only $5/acre. In this scenario, farmers would need to give up $24/acre to reduce RDR mean by 1.17 when going from VT2P to SmartStax® + Aztec®. Comparing VT2P + Aztec® to SmartStax® + Aztec®, to have RDR mean reduced by 0.53 farmers would need to give up $29/acre. In both crop insurance scenarios, the profits of the treatments using rootworm Bt traits were worse off by almost the same amount, and the treatments using non-rootworm Bt traits had their profits increased. In the 85% CL, this increase is more relevant, even having premiums way above the 70% CL.

The moral hazard opportunity in the pooled results with the 85% CL contract is associated with the fact that farmers would be more confident in using non-rootworm Bt traits to receive indemnities, as expected indemnities would be greater than premiums (as discussed by Just et al. 1999). In this context, farmers would be protected by the risk management tool to use treatments that do not require higher investments, even if those treatments leave them exposed to greater RDR. Because using only VT2P seed exposes farmers to great production risk in continuous corn, this treatment may not represent a realistic choice for farmers. Therefore, we could hypothesize that moral hazard is more likely associated with VT2P with Aztec®. If more farmers decide to use treatments with the VT2P seed because of the profitability provided by crop insurance, then on the regional level, the selection pressure provided by SmartStax® would be diminished, and the biotechnology could last longer as the pace at which WCR adapts may slow down. However, if farms are in an area that already has high Bt resistance levels, then using a rootworm-Bt hybrid that does not adequately control WCR would allow already resistant populations to increase, which in turn would speed up the biotechnology obsolescence. This scenario is why it is important to have the risk-reward analysis from the field groups' lenses, breaking apart fields by resistance levels and rootworm pressure, which is discussed next.

Table 5 presents the group that each field belonged to. Because the study was performed in areas with continuous corn, it is natural that most fields are in groups 1 and 3, where rootworm pressure is high (RDR ≥ 1 for VT2P). No field presented low rootworm pressure in 2021, which means groups 2 and 4 did not have fields assigned in that year. Even in other years, the number of observations (sites) is lower for those groups. Group 1 presents the greatest number of observations overall, but in 2020 it only had field number 7 representing the group. Because field 7 had issues with treatments that used the insecticide (they were inadvertently placed in non-irrigated areas), the entire field was not considered to allow fair comparison among treatments within group 1. Another thing to note is that comparison of treatments within groups can bring conclusive results, while comparison across groups for yields and profitability can be more challenging because of unbalanced number of fields, counties, and observations by year. One interesting fact is that only fields in areas with high resistance pressure received indemnities, which can suggest that ultimately rootworm population is the key variable that determines how areas will be affected, rather than current resistance levels per se. This result could potentially change in the future if resistance levels increase across the region. Pooled results and price simulation should take place, so plots by treatment from all years can be aggregated and the price dynamic process in the system can be incorporated.

6.1. Group 1 – HIGH/HIGH – High resistance/ High WCR density

Treatments in group 1 individually present the highest risk exposure when the same treatments are compared across groups in the no-insurance scenario (Figure 8). The control treatment (VT2P) has almost 2 nodes of injury on average (RDR mean = 1.92). The most profitable option, just like in the general results, is SmartStax®, which means that even when both pressure and resistance levels are high, adding the insecticide does not make a farmer better off from a profitability standpoint. However, risk exposure is reduced when Aztec® is added to SmartStax®, in this case to 0.23 RDR, which is the greatest trade-off reduction across treatments. At the same time, these two treatments that included rootworm Bt traits have their profitability further above the treatments using non-rootworm Bt traits than in the general results, which shows the benefit provided by the WCR biotechnology in group 1. The trade-off of adding the insecticide to SmartStax® decreases profitability by $14/acre (from $482/acre to $468/acre) for the 0.23 RDR mean reduction. Because it is the smallest profit reduction farmers need to accept when we compare to other groups, they may be encouraged to add the insecticide when fields belong to group 1, especially if those farmers have suffered from plant lodging before. For other price scenarios, the reduction in RDR shows a trade-off of a $19/acre profit reduction for low prices, and for high prices a $13/acre profit reduction.

When 70% CL and 85% CL are incorporated (Figure 8), the non-rootworm Bt treatments gain relevance because profitability approaches the other two treatments, which means crop insurance relatively reduces the benefit of the WCR biotechnology. For actual prices, VT2P + Aztec® and VT2P profits increase due crop insurance were $38/acre, and $34/acre, respectively. For low prices (Figure 9), increase in profits are $21/acre and $17/acre, and for high prices (Figure 10) $30/acre and $36/acre, respectively. The 85% CL, if strategically chosen by farmers, increases profitability for treatments using non-rootworm Bt traits and reduces it for the rootworm Bt traits.

Although in commercial fields it is unfeasible for farmers to measure resistance or population density levels because of the high costs of bioassays and experimentation, farmers intuitively perceive their risk exposure by observing and scouting the fields over the years. In theory, the awareness of the aggressiveness of WCR may motivate moral hazard decisions. By deciding not to use rootworm Bt traits, farmers in group 1 could face two possible scenarios: one is if the corrected bioassay survival approaches 1, a predominantly resistant population would multiply since few susceptible individuals are present. In that case, the farmer is left with almost no management options against resistance except to crop rotate to a non-WCR host to break the cycle of the pest. Some farmers might opt for population density management in which, given the high resistance level, they try to bring fields from group 1 to group 2 by controlling the adult population (and egg laying in the following year) with the use of a foliar insecticide. However, if the corrected bioassay survival is around 0.5, there is still a significant number of susceptible individuals present so periodic planting of VT2P + Aztec® would reduce selection pressure from the pyramid and possibly slow the evolution of resistance.

6.2. Group 2 – HIGH/LOW - High resistance/ Low WCR density

Group 2, although having fields in high resistance areas, does not present high rootworm pressure, and the most profitable treatments are the ones that use non-rootworm Bt seeds (Figure 11). Because group 2 does not get indemnities, Figure 11 only displays the no insurance scenario. From a profitability standpoint, farmers in this group are better off not investing in non-rootworm Bt seeds, even knowing the resistance level is high. The rootworm Bt seeds do not bring high enough yields to compensate for higher costs. Curiously, field 8 does not get indemnity in 2021, the year that it is classified as Group 2. In 2020 and 2022, field 8 presents high rootworm pressure, makes it to Group 3, and gets indemnity in both years.

As for the trade-offs, all treatments present very similar RDR levels, which indicates root damage is more associated with population density than with current resistance levels. VT2P + Aztec® and SmartStax® present the same level of RDR mean (a low level of 0.19), which means that the biotechnology and the insecticide provide similar effects in reducing risk exposure, but the use of the insecticide is notable because in other groups VT2P + Aztec® has higher risk exposure compared to SmartStax®. The only trade-off in group 2 is between using the insecticide with VT2P or with SmartStax®. This result is indicative that the root protection provided by the insecticide is very efficient to shield corn crops from a resistant, yet low-density, population. This result is reinforced by the fact this is the only group where SmartStax® + Aztec® is more profitable than SmartStax® ($45/acre difference), even considering both treatments have very similar mean RDR. If we simulate low prices, this difference between treatments is $64/acre, which brings farmers out of the negative profitability zone. For high prices, the difference is $96/acre.

When the same price is applied in all years, VT2P + Aztec® stands out, and the insecticide effect brings more profit than VT2P alone (an extra of $4/acre in the low-price scenario – Figure 12 - and $28/acre in the high price scenario – Figure 13). As none of group 2's fields got indemnities, the 70% CL premiums would represent an average profit deduction of $4/acre for each treatment. The 85% CL may not be purchased by farmers as they would not incur high premiums when resistance pressure is low, and indemnities are not expected.

6.3. Group 3 – LOW/HIGH – Low-moderate resistance/ High WCR density

Group 3 has fields assigned every year. Fields are in a low resistance area but present high rootworm pressure, and risk exposure by treatment is similar to group 1. The most profitable treatment is SmartStax®, followed by VT2P + Aztec® (Figure 14). Different from group 1, VT2P + Aztec® performs better than SmartStax® + Aztec®, which means that in group 3, two trade-offs can be identified. One trade-off is between adding the insecticide to SmartStax®, which would reduce profitability by $74/acre to reduce mean RDR only by 0.12. For the low-price scenarios, this difference would be $54/acre, although all treatments would have had at least $100/acre negative profitability. When price simulation is run with the low price, group 3 is the most harmed among treatments. For the high-price scenario, the difference would get back to $75/acre. The second trade-off is between using the insecticide with VT2P or with SmartStax®. For actual prices, the difference is $21/acre for a mean RDR reduction of 0.75, for low prices $26/acre (although all negative profits) (Figure 15), and for high prices only $12/acre (Figure 16).

When we look at the standard 70% CL, trade-offs are not much impacted, except for the profitability increase for VT2P treatments, which made it slightly more profitable than SmartStax® + Aztec®, but still less than the other treatments. Now, just like in group 1, if farmers are generally aware of their WCR problems, then the 85% CL could be purchased strategically by them. In doing so, treatments using non-rootworm Bt traits become more profitable than the ones using rootworm biotechnology. Again, moral hazard implications would be associated to VT2P + Aztec®, assuming farmers would never choose to be completely unprotected from WCR in areas of continuous corn. Looking at actual prices (Figure 14), the profits increase is $82/acre for VT2P + Aztec® and $192/acre for VT2P. For low prices (Figure 15), the profits increase are $44/acre and $118/acre, and for high prices they are $94/acre and $221/acre (Figure 16), respectively. This group is the most impacted by crop insurance.

In the moral hazard scenario, the areas under group 3 that present corrected bioassay survival below 0.5 would see susceptible WCR individuals reproducing over the years by using non-rootworm Bt traits: because of the reduced selection pressure of not using SmartStax®, the obsolescence of the product would be delayed, and its effectiveness could last longer in the market. In this case, crop insurance would unintendedly be motivating farmers to plant VT2P + Aztec®, which from a resistance management standpoint is a positive scenario to delay resistance evolution. It offers a benefit in two directions: by having a lack of incentive to guard against risk exposure farmers would receive indemnities and also attenuate selection pressure.

6.4. Group 4 – LOW/LOW - Low resistance/ Low-moderate WCR density

Group 4 has fields in low-resistance areas that present low rootworm pressure (low population density). Its most profitable treatment is also SmartStax® (Figure 17). This result is somewhat unexpected considering that for group 3 - which fields were also in low resistant areas - SmartStax® was the least profitable option. What we would expect is that when the rootworm pressure is low, especially when accompanied by low resistance, SmartStax® would not be so profitable, and that treatments using VT2P seeds would stand out.

There are some things to consider that can help explain this phenomenon. The first one is that group 4 is the group with the least profit differences across treatments, which ultimately came down to a matter of cost difference. Still, in this case, we would expect SmartStax® to have lower profitability than what it had. Although uncertain why SmartStax® played a role in increasing profits to group 4, one thing that can be considered is the fact that group 4 presents low levels of root damage overall for all treatments, especially for rootworm-Bt traits, which could have allowed the corn to develop nearly damage-free for all treatments. Consequently, the comparison among treatments would come to be a matter of input costs.

For the low-price scenario, all treatments have negative profits (Figure 18). For the high-price scenario, the SmartStax® treatment has profits of $615/acre and the SmartStax® +Aztec® treatment has profits of $498/acre (Figure 19).

6.5. Groups Comparison

When we compare the risk-reward analysis across groups (all groups plotted together), there are a few things we can observe and consider. For actual prices (Figure 20), groups

1 and 2, high resistance fields, obtain higher profitability than groups 3 and 4, low resistance fields. This result is because, given the unbalanced nature of the dataset, the group average is affected by the years that have higher or lower prices. Group 1, for example, only had fields in the years 2021 and 2022, which means that the pooled results are not being driven down by having 2020 included (a year of low prices).

We then consider low and high price scenarios where profitability would depend exclusively on treatment's cost and yields, by group. For both low prices and high prices (Figures 21 and 22, respectively), we can see that now group 2 has the highest profitability, followed by group 1, then by group 4, and last by group 3. Because we have hypothesized that WCR population density plays a more important role in determining profitability than current resistance levels, it is expected that groups with low population density (groups 2 and 4) to be more profitable than groups with high population density (groups 1 and 3).

What could seem counterintuitive is that group 1 (HIGH/HIGH) presented similar profit levels to group 4 (LOW/LOW). This result is because group 1 obtained higher yields than group 4. Figure 23 shows the yield levels by group. It is important to remember that even though prices across years used in this analysis are the same, yields are still determined in different years across groups, which could have resulted in year-specific unobservable variables affecting the fields regardless of treatments, resistance levels, or WCR population. Groups 2 and 4 for example, do not have yields determined in year 2021. Group 3 has more plots assigned in 2020 and 2021 than in 2022 (only one plot assigned). Group 4 does not have plots assigned in 2020.

When all observations are pooled together by group, ultimately the profitability ranking comes down to the yield ranking. Group 3 has the poorest productivity performance (which is also why it is the group to receive more indemnities when yields are compared to the APH). Group 1 also gets indemnities, but its impact is not as great as in group 3 because it presented better productivity, so the difference to their APH is smaller. Group 4 does not perform better than group 3, even having the best WCR conditions to do so.

When we look only at the low corn price scenario, most groups and treatments have negative profits, except for the treatments of groups with high resistance levels: SmartStax® for group 1, and treatments using VT2P for group 2. Also, when corn prices are low for three years in a row, not even indemnities from the 85% CL are able to add revenue to groups 1 and 3 to take them out of the negative profitability zone.

Now, when we look at the high corn price scenario, the profit differences across groups increase. Because of that, we can see VT2P + Aztec® for group 2 (the best-performing combination of treatment and group) obtains over $600 per acre more than VT2P for group 3 (the worst-performing combination of treatment and group). This difference is not even $300 per acre in the low-price scenario. We can also observe the benefit provided by the WCR biotechnology: SmartStax® and SmartStax® + Aztec® in group 1 (HIGH/HIGH) have higher profits than V2TP and VT2P + Aztec® in group 4 (LOW/LOW), the two riskier options. Also, in this scenario, we can see again the impact generated by indemnities: the VT2P treatments for groups 1 and 3 receive $221/acre and $43/acre respectively. For group 3, this addition, in all price scenarios, brings VT2P to the same profit levels as to VT2P + Aztec®. For actual and low corn price scenarios, VT2P becomes the most profitable treatment within the group. For group 1, VT2P becomes more profitable with crop insurance than VT2P and VT2P + Aztec® from group 4 (LOW/LOW), even in a HIGH/HIGH environment. Figure 24 provides a summary of the actual impact of different CLs for all groups by treatment under the different crop insurance scenarios.

7. Conclusions

In this study, we do an economic analysis using field experimental data conducted on western corn rootworm in Northeast Nebraska focused on *ex-ante* Integrated Pest Management in continuous cornfields, using 4 different treatments against this pest across the years 2020, 2021, and 2022. We found that in all years, SmartStax® (Cry3Bb1 + Cry34/35Ab1 hybrid) is the most profitable option, which means that the WCR Bt technology is still effective. Using the insecticide with SmartStax® is not as profitable as using it with VT2P: overall the insecticide is yield-reducing and a profit-reducing factor for SmartStax® and a yield-increasing and profit-increasing factor for VT2P.

The dynamic changes once risk exposure was incorporated. The risk-reward analysis shows a trade-off in all three years: farmers that want to reduce risk exposure would have to accept $36/acre less if they wanted to reduce mean RDR by 0.14, by adding the insecticide to SmartStax®. SmartStax® + Aztec® greatly reduces plant lodging through root protection, which would be an option to farmers with a history of yield loss due to plant lodging (which is not covered in this analysis because yields were hand-harvested in the experiments). We also compared how much farmers would need to give up if they switched from VT2P + Aztec® to SmartStax® + Aztec®: profits would decrease $11/acre, but mean RDR would be reduced by 0.53. VT2P was by far the option with the highest risk exposure, as it does not offer any activity against WCR. Trade-offs' influence on farmers' decision-making depends on the degree that farmers are willing to give up on profits to reduce RDR. This degree is unknown since behavior was not modeled in this study.

When crop insurance is incorporated into the analysis, the trade-offs are greatly impacted. Given risk exposure does not change, differences in profits are tighter, as WCR Bt treatments' profitability decrease and the non-WCR Bt treatments' profitability increase. If before crop insurance is incorporated the difference between the most and least profitable options (SmartStax® vs VT2P) is $52/acre, after crop insurance this difference shrinks to $27/acre at the 70% CL and to $10/acre at the 85% CL. These new calculated differences might not be economically significant, indicating a farmer, from a profitability perspective only, could be indifferent among treatments. This claim is especially true for the 85% CL, characterizing the moral hazard situation.

When fields' resistance levels and population densities are accounted for, all treatments that use non-WCR Bt treatments gain an advantage. Our results also suggest that rootworm pressure is more important in creating moral hazard than resistance levels, as only groups 1 and 3 received indemnities. The moral hazard strategy can be even more predominant in years when prices are high because it creates greater impacts from indemnities. In this context, if resistance is low-moderate (corrected bioassays survival approaches 0.5 - group 1 - or is below 0.5 – group 3), crop insurance might unintendedly motivate farmers to plant non-WCR Bt treatments. The outcome would offer a benefit in two directions: by having a lack of incentive to guard against risk exposure farmers would receive indemnities and also attenuate selective pressure. Therefore, the WCR Bt technology’s effectiveness would last longer, and its obsolescence could be delayed. However, if corrected survival approaches 1, resistance is so high that farmers have two options: they either try to control the adult population with foliar insecticide to temporarily bring fields from group 1 to group 2, or they need to crop rotate to a non-WCR host, like soybeans.

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Figures

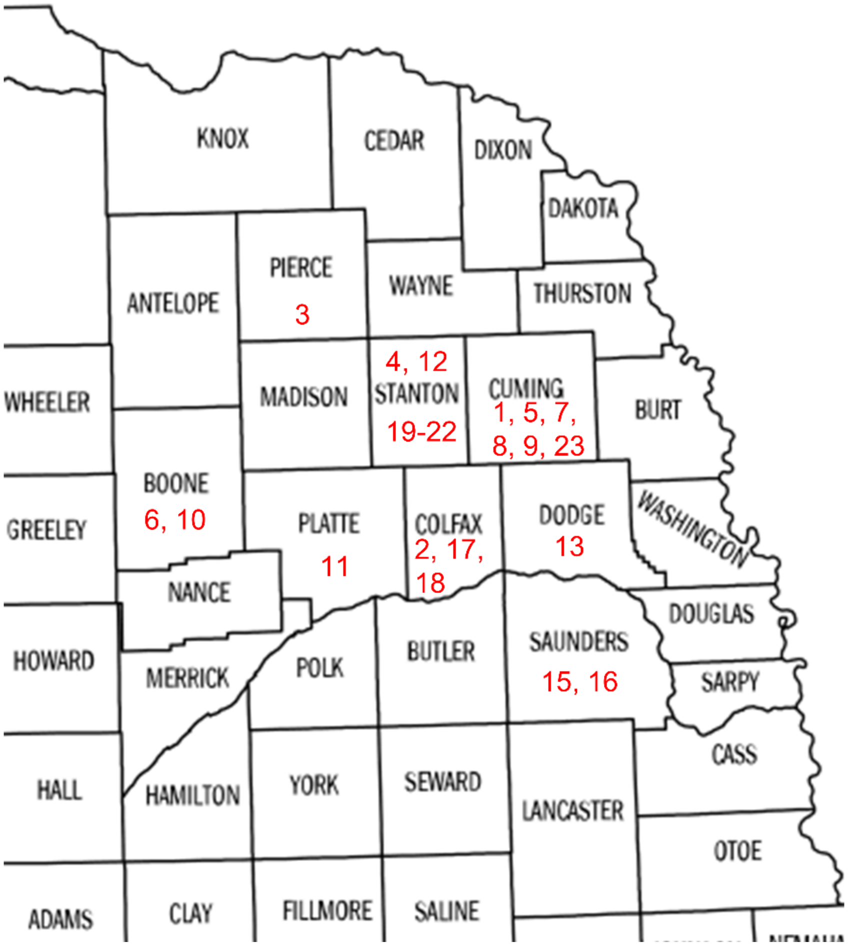

Figure 1: County map of northeast Nebraska. Red numbers within each county denote the unique number assigned to each field/WCR population used in the project.

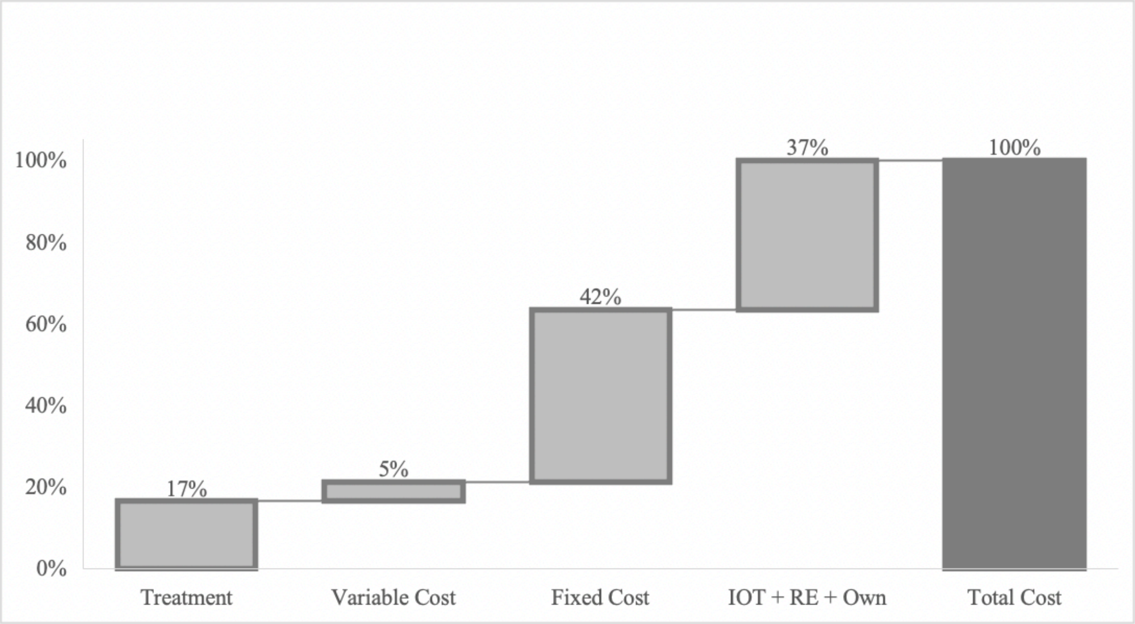

Figure 2: Total Cost of Production Composition

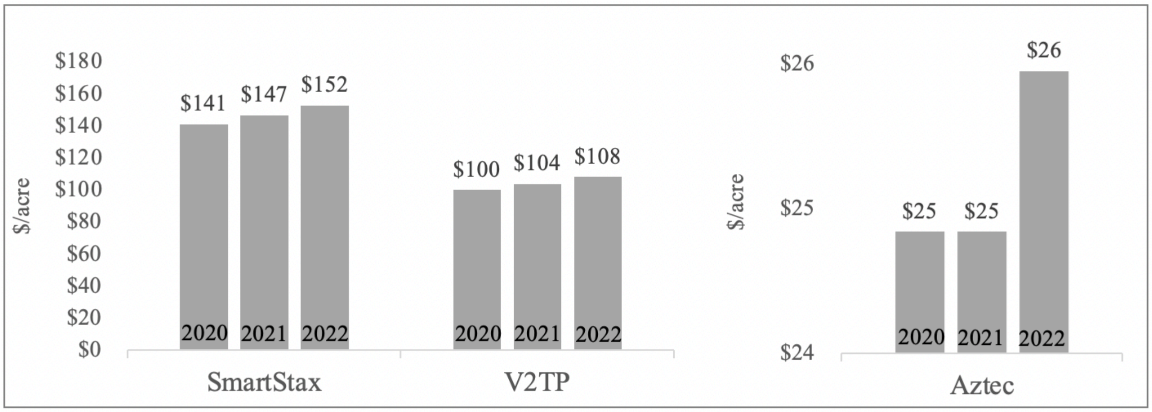

Figure 3: Treatment's Input prices

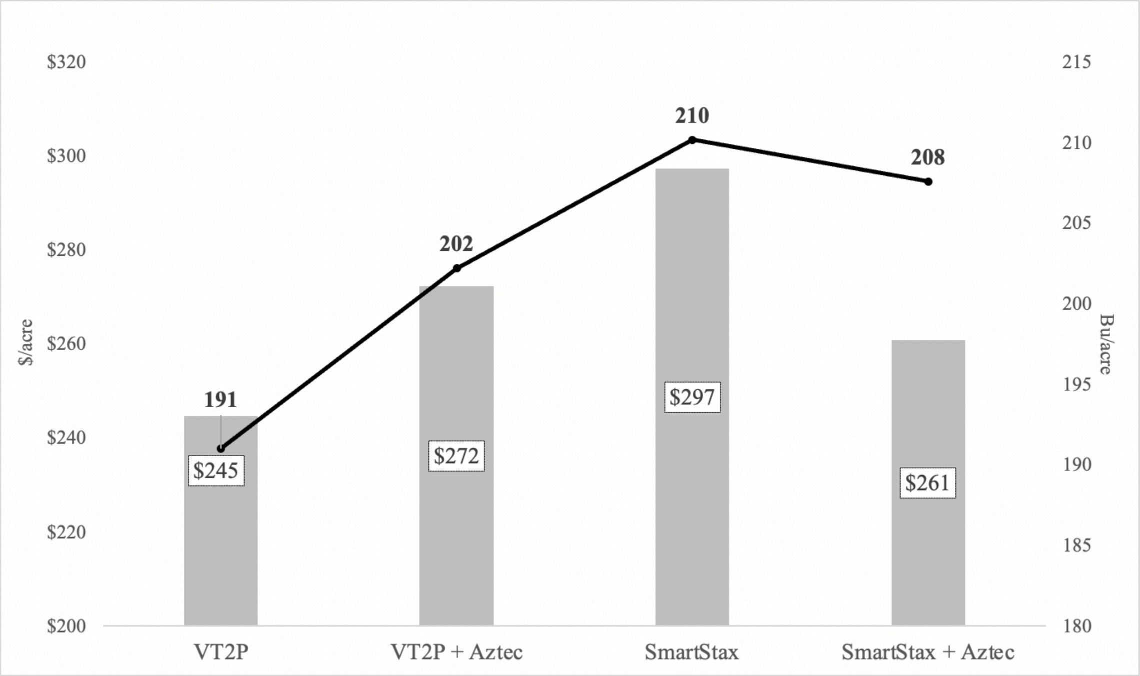

Figure 4: Profitability and Productivity by Treatment – Pooled Years.

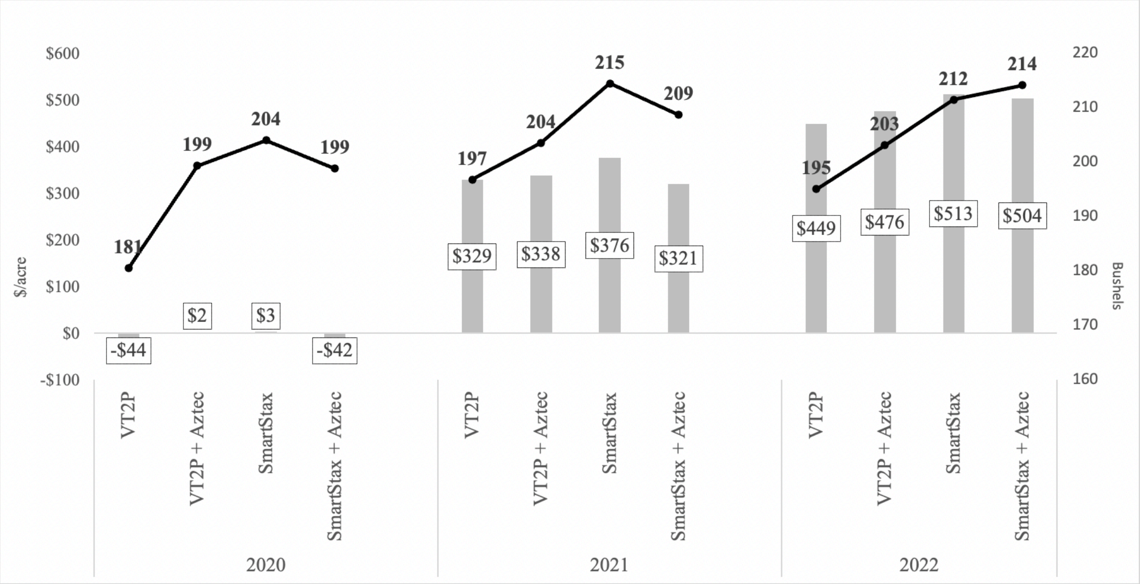

Figure 5: Profitability and Productivity by Treatment – and by Year.

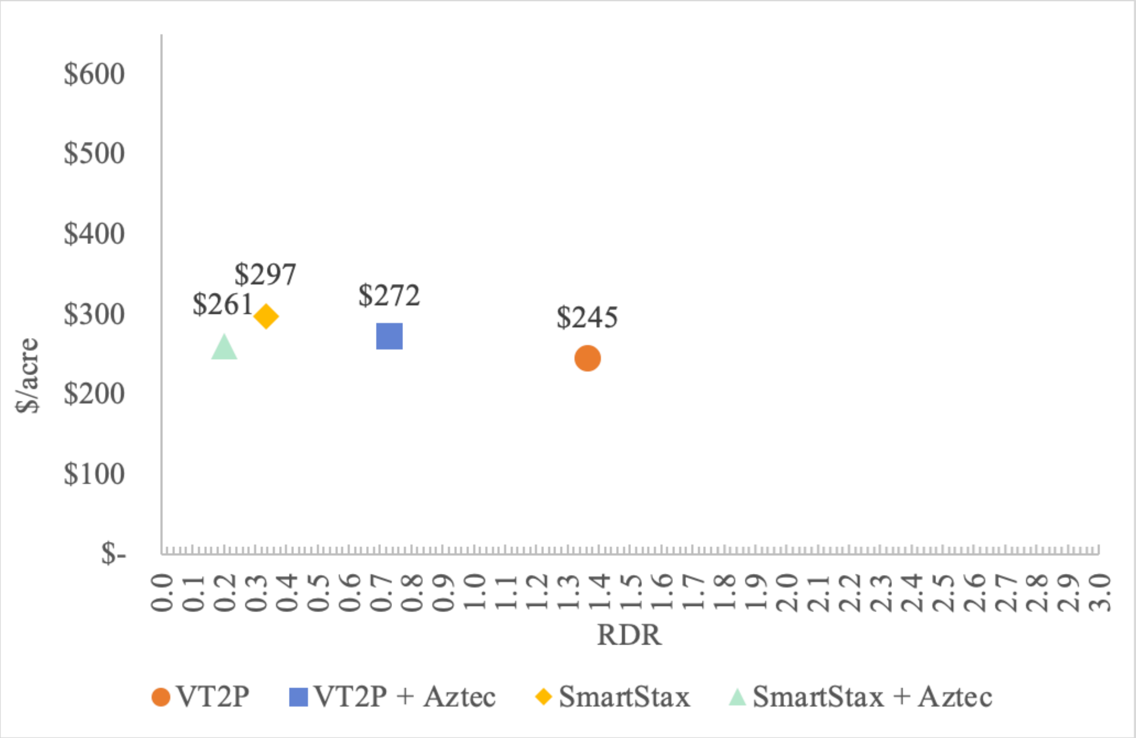

Figure 6: Risk-Reward Analysis – Pooled Years

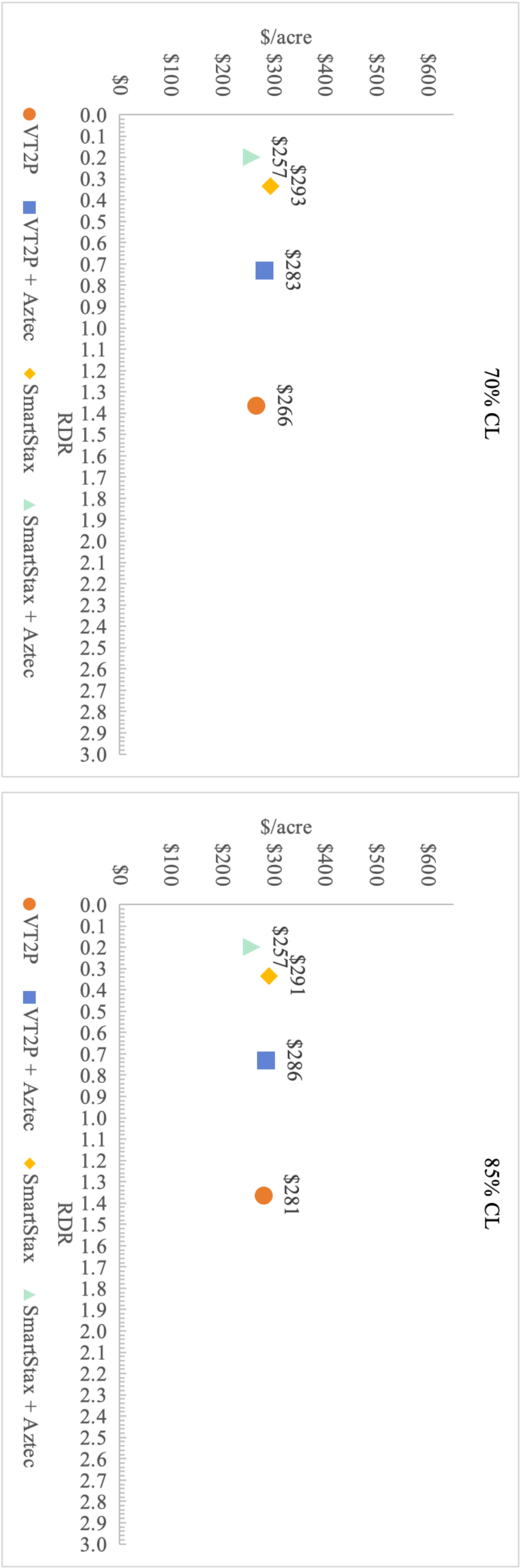

Figure 7: Risk-Reward Analysis Under Different Coverage Levels – Pooled Years

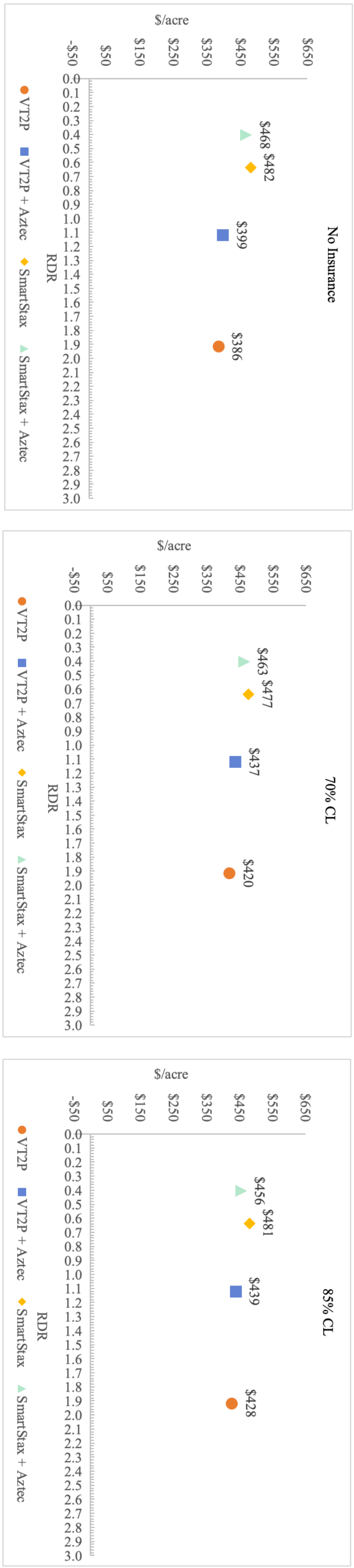

Figure 8: Risk-Reward Analysis for different coverage level scenarios – Group 1 – Pooled Years – Actual Prices

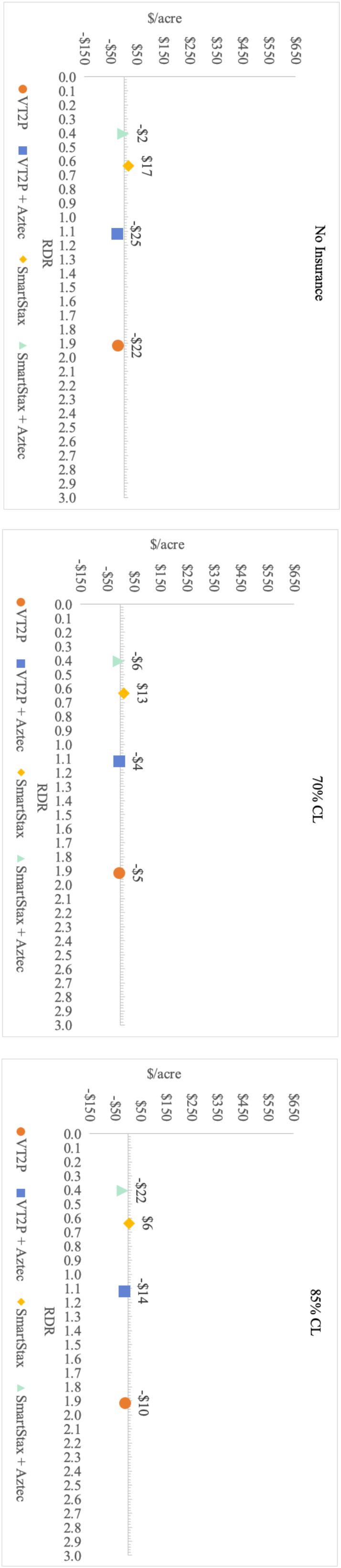

Figure 9: Risk-Reward Analysis for different coverage level scenarios – Group 1 – Pooled Years – Low Price

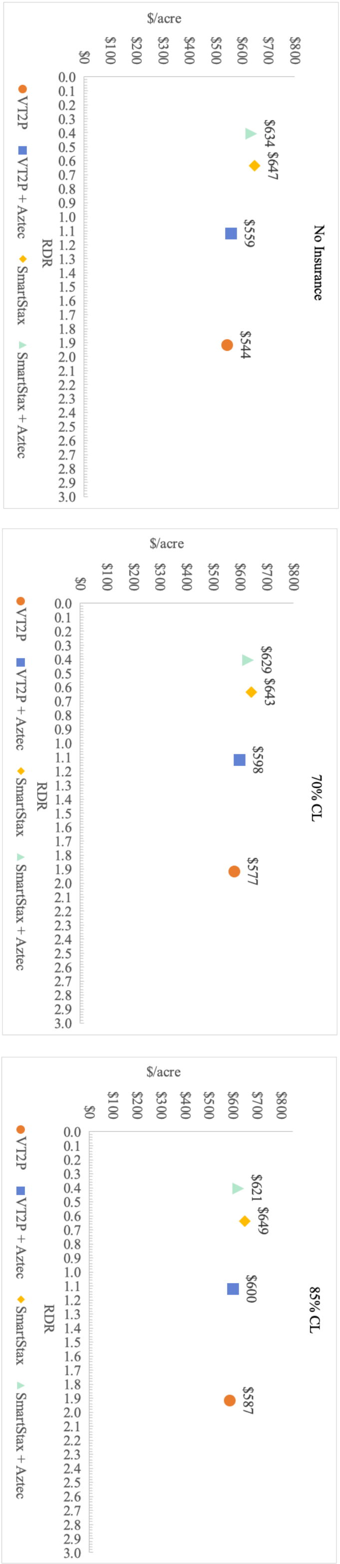

Figure 10: Risk-Reward Analysis for different coverage level scenarios – Group 1 – Pooled Years – High Price

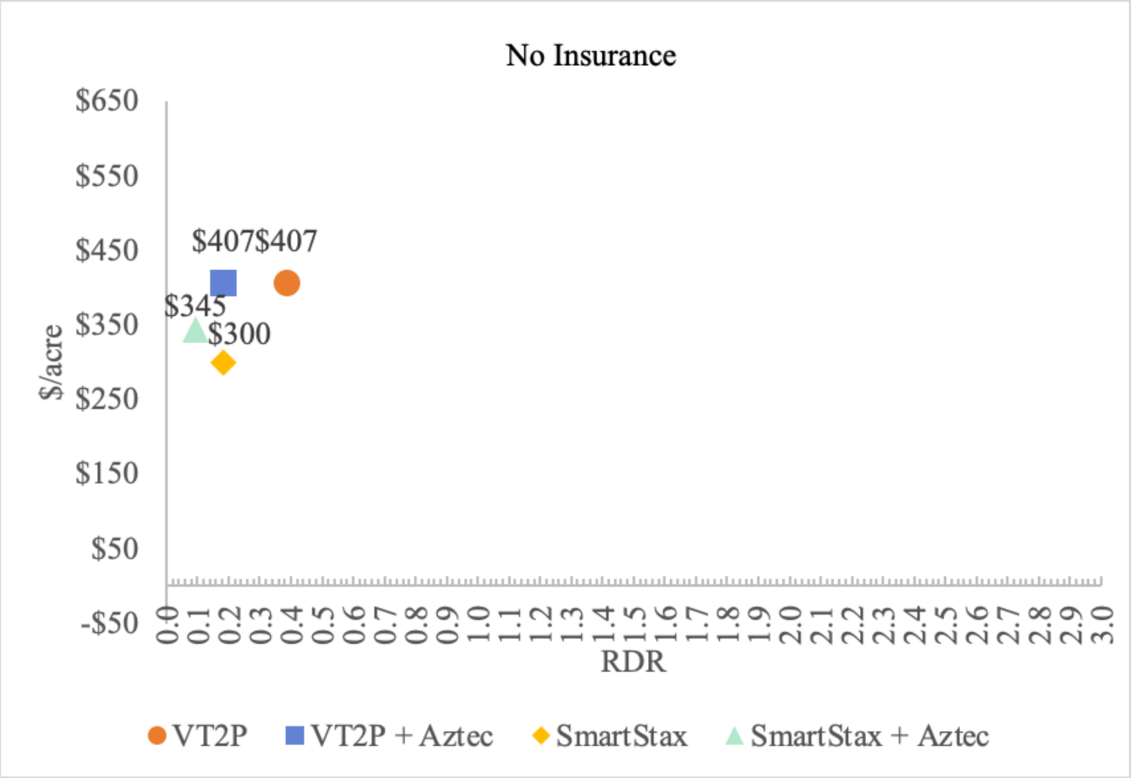

Figure 11: Risk-Reward Analysis – Group 2 – Pooled Years – Actual Prices

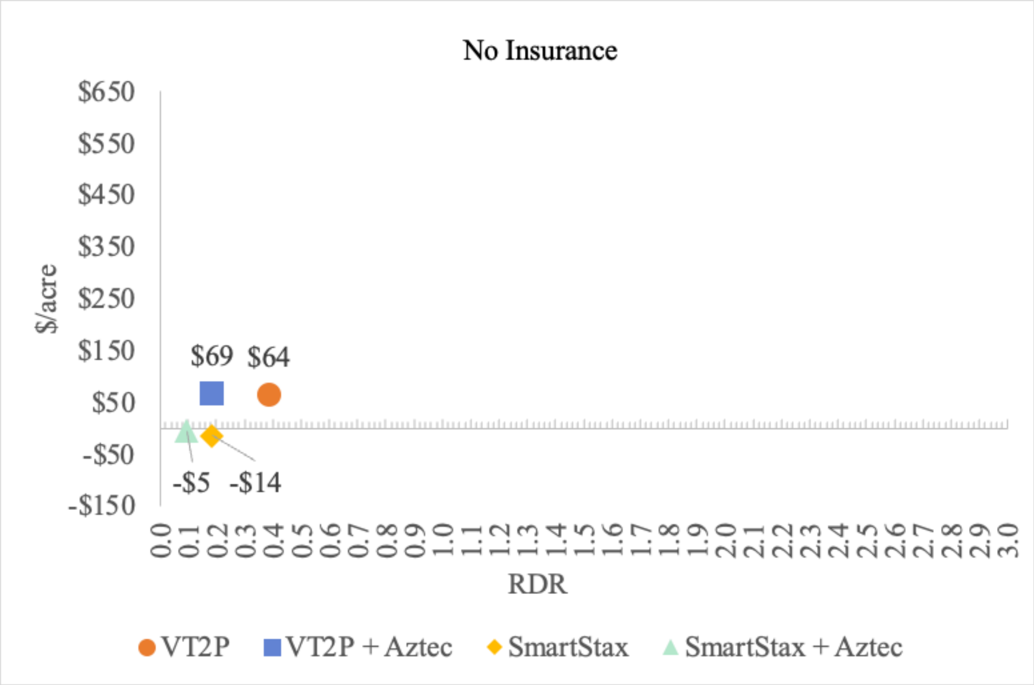

Figure 12: Risk-Reward Analysis – Group 2 – Pooled Years – Low Price

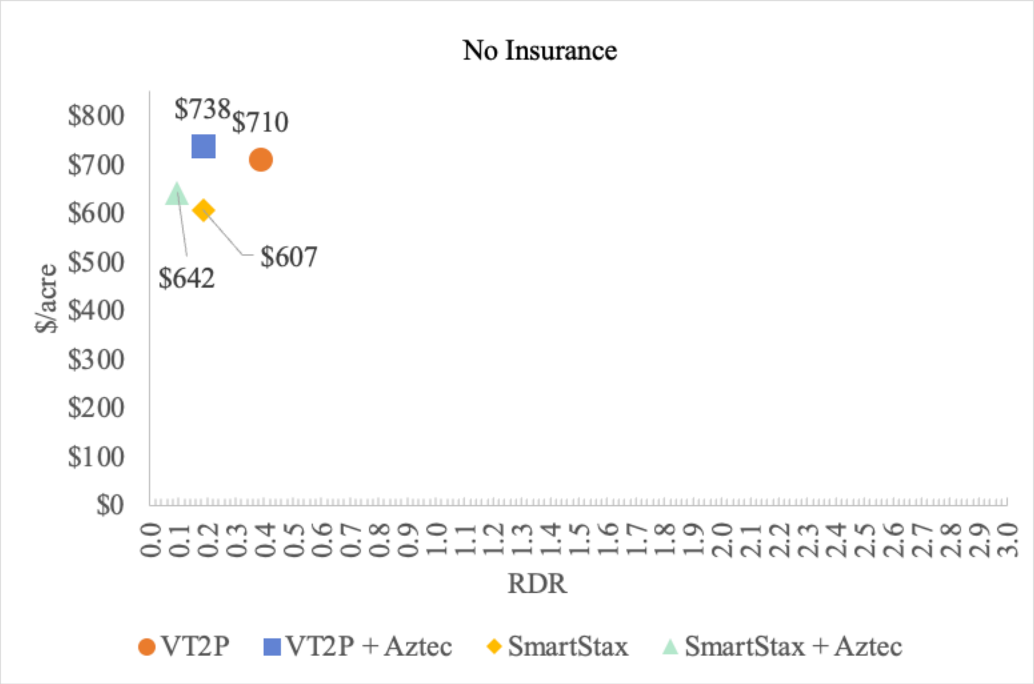

Figure 13: Risk-Reward Analysis – Group 2 – Pooled Years – High Price

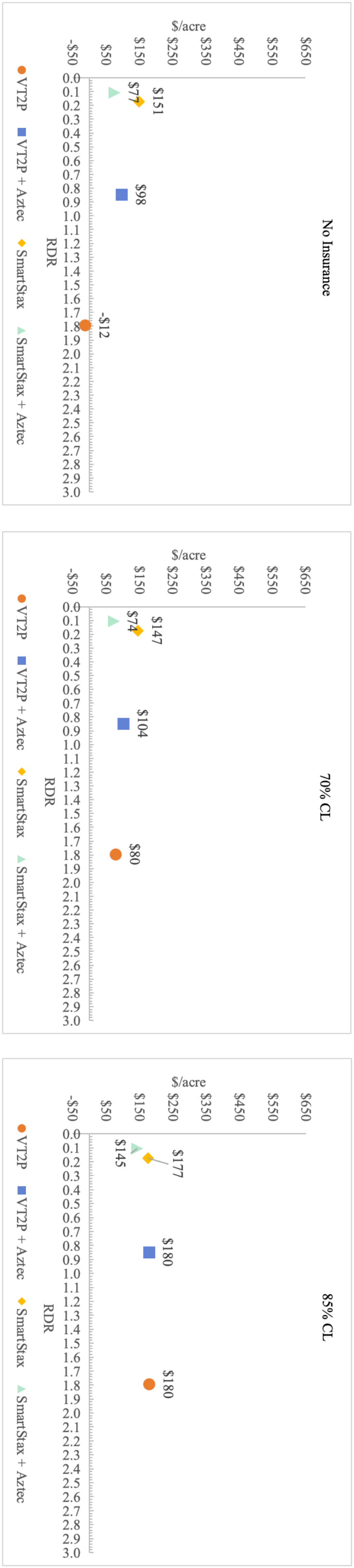

Figure 14: Risk-Reward Analysis for different coverage level scenarios – Group 3 – Pooled Years – Actual Prices

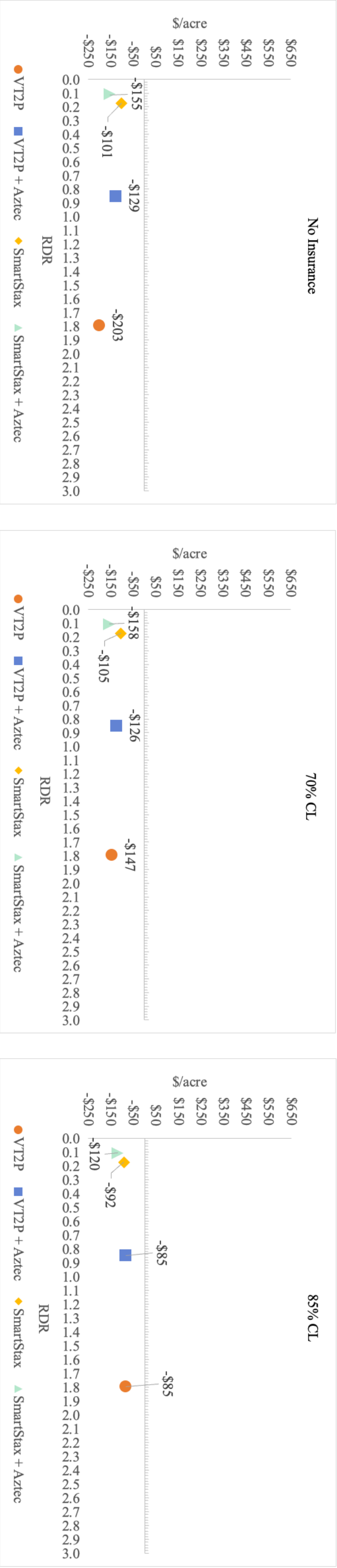

Figure 15: Risk-Reward Analysis for different coverage level scenarios – Group 3 – Pooled Years – Low Price

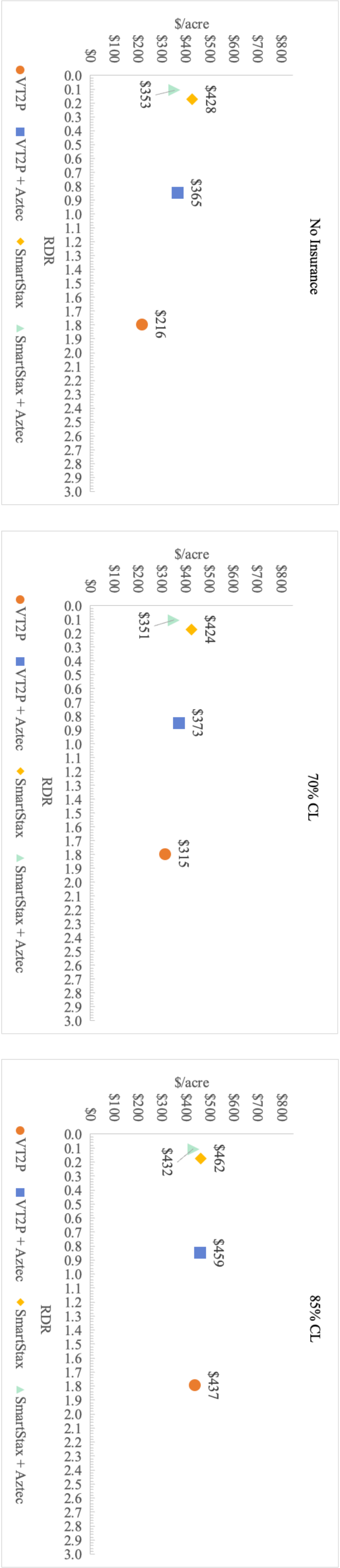

Figure 16: Risk-Reward Analysis for different coverage level scenarios – Group 3 – Pooled Years – High Price

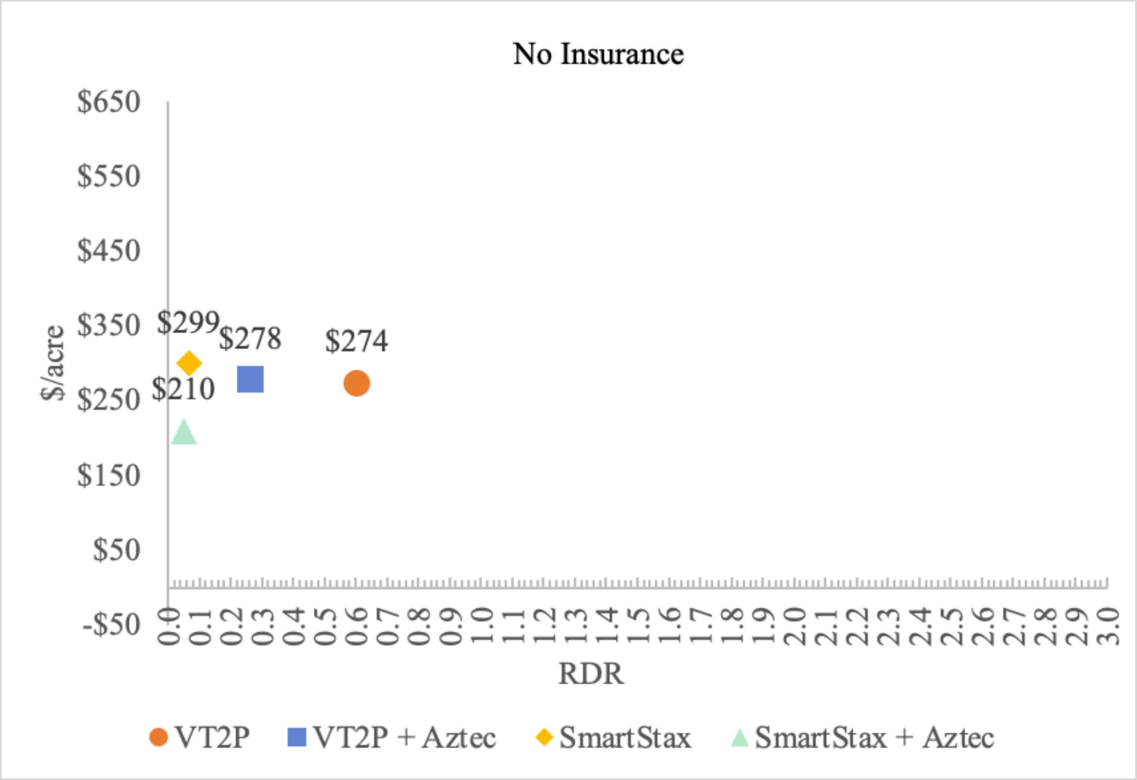

Figure 17: Risk-Reward Analysis – Group 4 – Pooled Years – Actual Prices

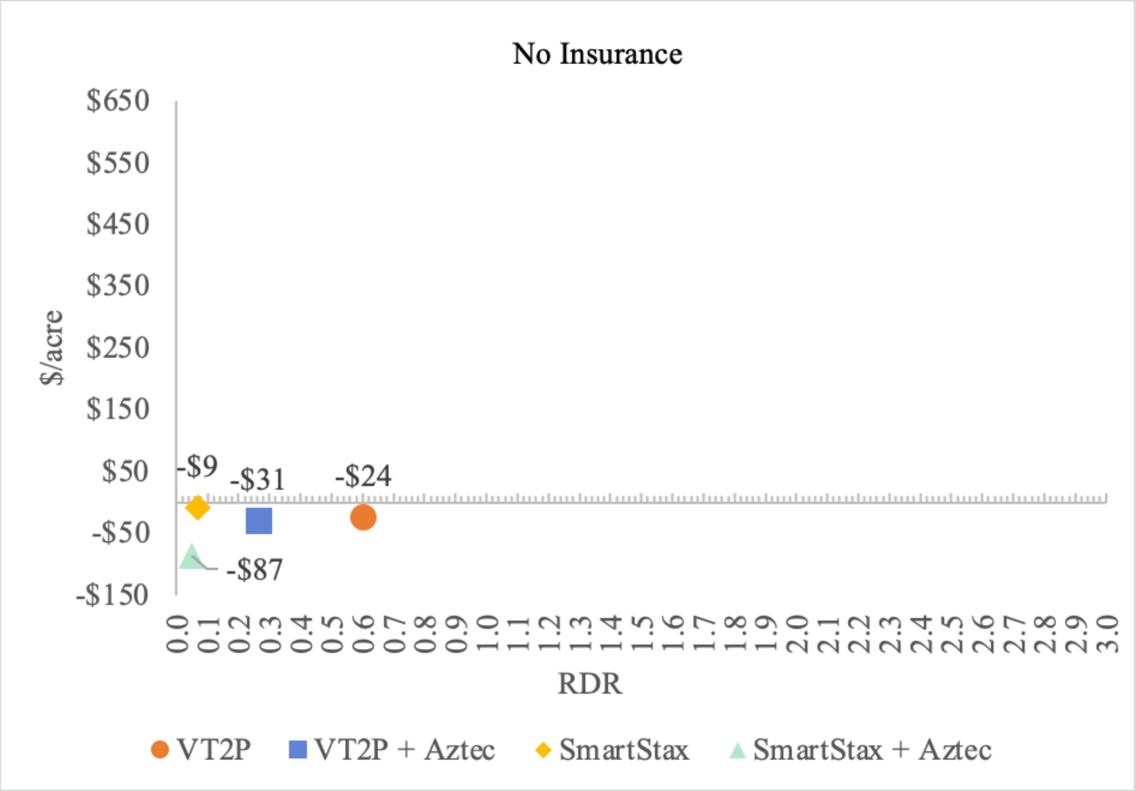

Figure 18: Risk-Reward Analysis – Group 4 – Pooled Years – Low Price

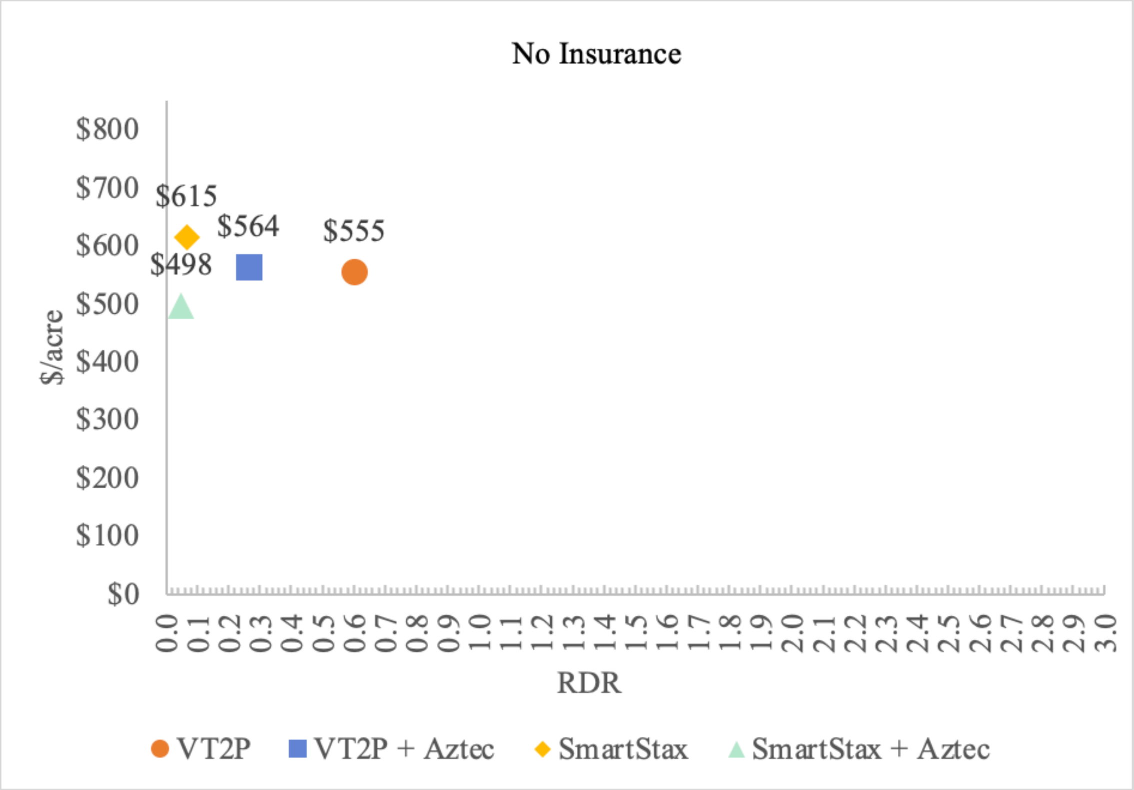

Figure 19: Risk-Reward Analysis – Group 4 – Pooled Years – High Price

VT - VT2P
VT + A - VT2P + Aztec
SS - SmartStax
SS + A - SmartStax + Aztec

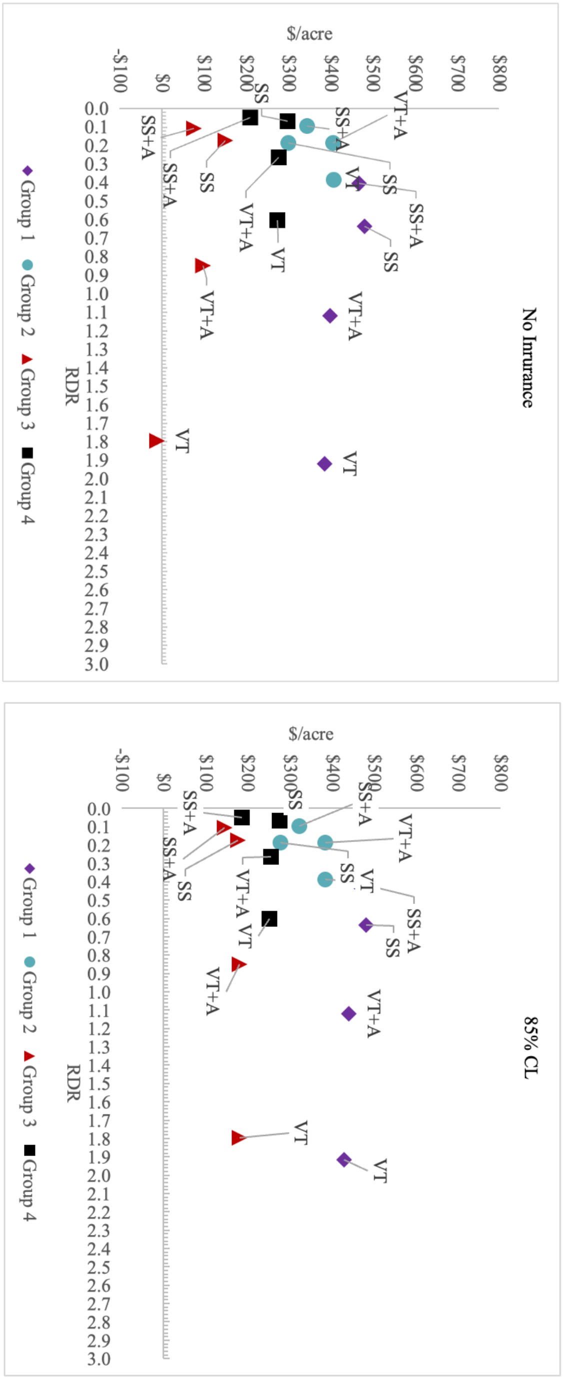

Figure 20: Risk-Reward Analysis by Group and Treatment in Different Crop Insurance Scenarios – Pooled Years - Actual Prices

VT - VT2P
VT + A - VT2P + Aztec
SS - SmartStax
SS + A - SmartStax + Aztec

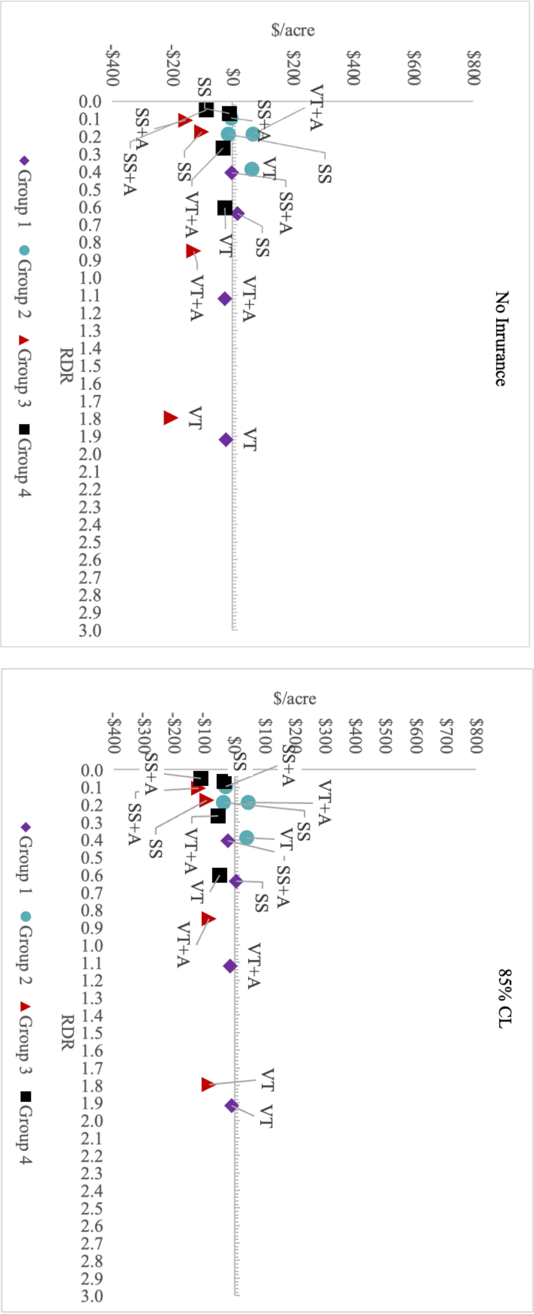

Figure 21: Risk-Reward Analysis by Group and Treatment in Different Crop Insurance Scenarios – Pooled Years - Low Prices

VT - VT2P
VT + A - VT2P + Aztec
SS - SmartStax
SS + A - SmartStax + Aztec

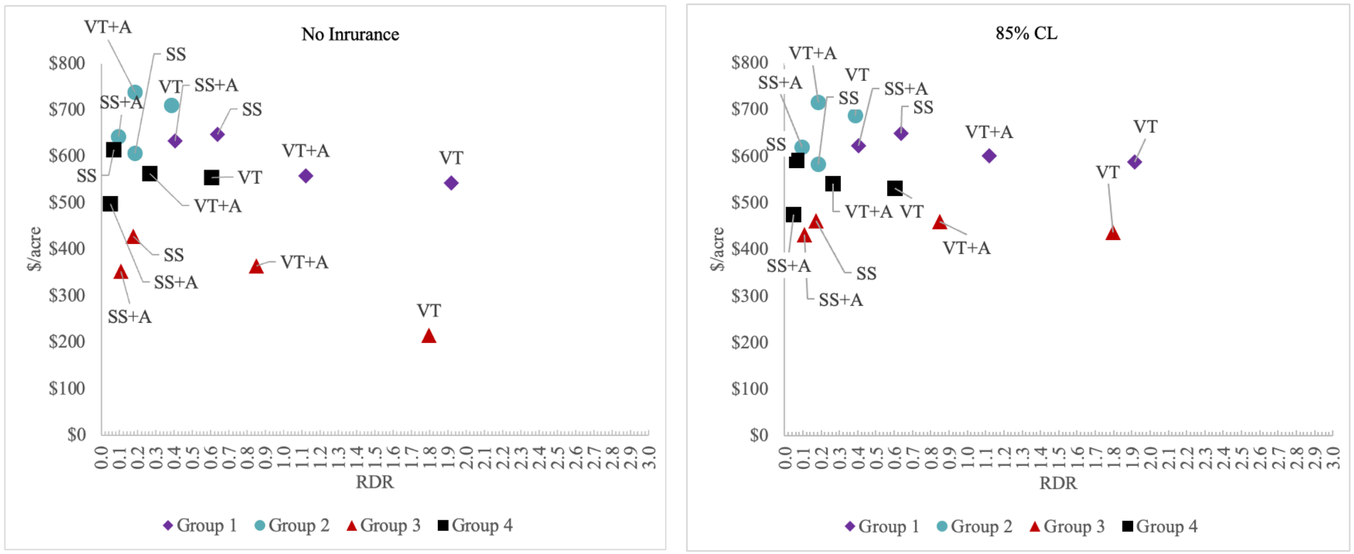

Figure 22: Risk-Reward Analysis by Group and Treatment in Different Crop Insurance Scenarios – Pooled Years - High Prices

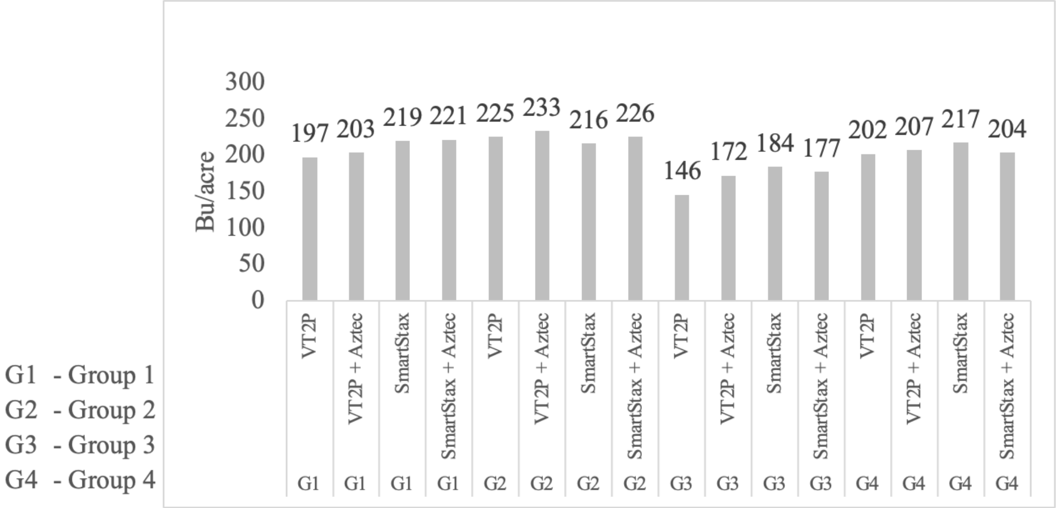

Figure 23: Yield by Group and Treatment

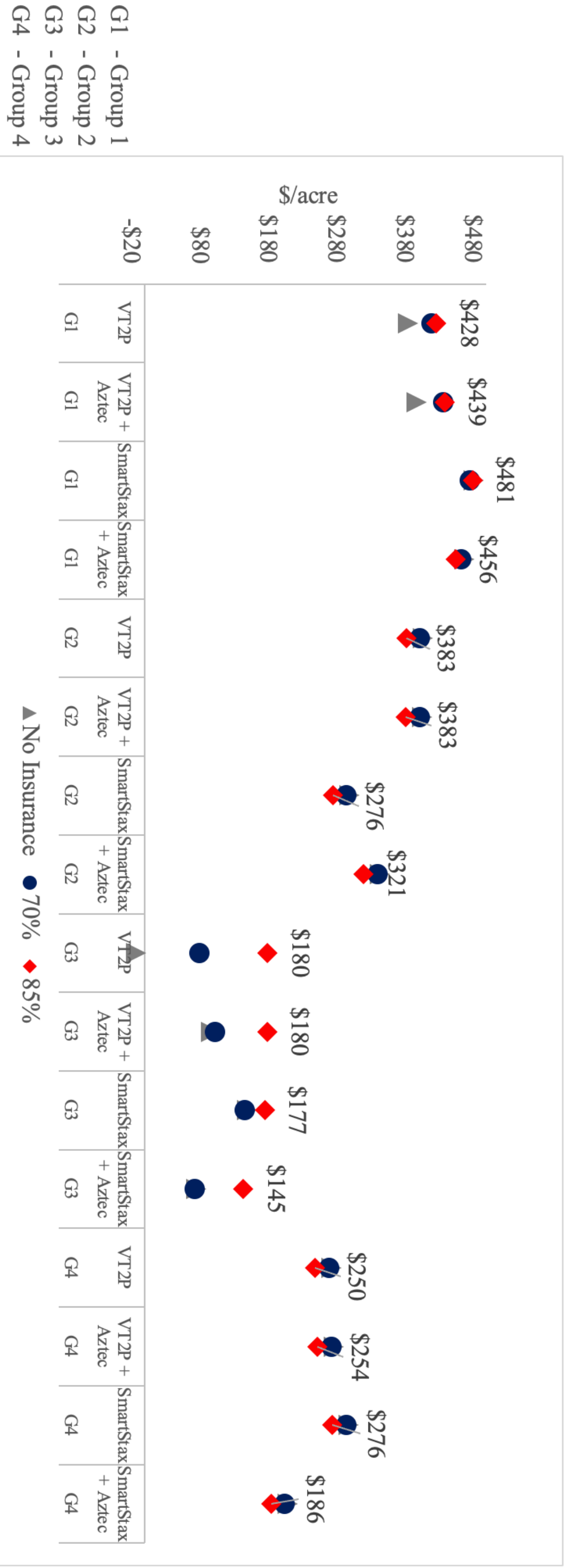

Figure 24: Profitability by Group and Treatment in Different Crop Insurance Scenarios – Pooled Years - Actual Prices

Tables

Table 1: Fields identified by number, their respective county, and year

YEAR	BOONE	COLFAX	CUMING	DODGE	PIERCE	SAUNDERS	STANTON
2020	6, 10	2	7, 8	13	3	15, 16	12
2021	6, 10	2,17	7, 8, 9	-	3	15, 16	12
2022	10	2,18	7, 8, 9	-	3	15, 16	19

Table 2: Projected and Harvest Prices in $/bushel by year

Year	Projected Price	Harvest Price
2020	$3.88	$3.99 *(used for the low-price scenario)*
2021	$4.58	$5.37
2022	$5.90	$6.86 *(used for the high-price scenario)*

Table 3: Crop Insurance Coverage Level Premiums in $/acre by year

Year	70%	85%
2020	$2.31	$13.11
2021	$4.21	$26.86
2022	$5.44	$34.70

Table 4: Fields that got Indemnities at the 70% and 85% Coverage Levels

		2020	2021	2022
70% CL	VT2P	15	15	10, 15
	VT2P + Aztec®	-	6	10, 15
	SmartStax®	-	-	-
	SmartStax® + Aztec®	-	6	-
85% CL	VT2P	6,12,15	6,8,10,15,16	10,15,18
	VT2P + Aztec®	12,15	6	10,15
	SmartStax®	15	6,10	10,15
	SmartStax® + Aztec®	15	6, 15	10,15

Table 5: Fields by Group and Year, by Treatment

		2020	2021	2022
Group 1	VT2P	7	2 7 **8*** 9 **10*** 12 17	7 9 **10*** 12 **18***
	VT2P + Aztec	7	2 7 8 9 10 12 17	7 9 **10*** 12 18
	SmartStax	7	2 7 8 9 **10*** 12 17	7 9 **10*** 12 18
	SmartStax + Aztec	7	2 7 8 9 10 12 17	7 9 **10*** 12 18
Group 2	VT2P	8 10		8 19
	VT2P + Aztec	8 10		8 19
	SmartStax	8 10		8 19
	SmartStax + Aztec	8 10		8 19
Group 3	VT2P	2 **6*** **12*** **15***	3 **6*** **15*** **16***	**15***
	VT2P + Aztec	2 6 **12*** **15***	3 **6*** 15 16	**15***
	SmartStax	2 6 12 **15***	3 **6*** 15 16	**15***
	SmartStax + Aztec	2 6 12 **15***	3 **6*** **15*** 16	**15***
Group 4	VT2P	3 13 16		2 3 16
	VT2P + Aztec	3 13 16		2 3 16
	SmartStax	3 13 16		2 3 16
	SmartStax + Aztec	3 13 16		2 3 16

***Plots that got indemnities at the 85% CL**

Appendix

Field Operations and their costs

1 - Spray spring burndown herbicide

Farmers evaluate the area during Spring before considering incurring the costs of burning down the whole corn field for planting no-till. On average, a farmer would only burn down the area every other year, so for the annual budget, a 50% application factor was considered. For this operation, there is the cost of application (labor, fuel, and repairs) and cost of input (quantity used and price per quantity).

To obtain the cost of labor for burning down the area, an average of 33 acres per hour was considered for a medium tractor, with a labor factor of 1.25 and a wage rate of $25 per hour (which was kept the same across 2020, 2021 and 2022). To calculate the cost per acre of labor for this operation we divided the labor factor by unit per hour per acre and multiplied by wage rate and quantity (50% of the time).

The cost of fuel was calculated by multiplying the diesel use per hour for the same medium tractor (2.64 gallons) by diesel and lube price ($2.61/gallon for 2020, $1.73/gallon in 2021, and $3.24/gallon in 2022) and dividing the result by units per hour (33 acres/hour).

The cost of repairs is split in Power cost and Implement cost. Power is the cost per acre given by the calculated value of the tractor at the beginning of the year (incorporating the age of the tractor – in this case assuming 5 years of age – and depreciation) divided by units per hour. Implement cost is the cost of repair per acre calculated based on the annual use, estimated life, list price ($48.000 for 2020), and units per hour.

2 - Herbicide application before planting

Farmers are oriented to not skip the pre-emergence herbicide, so this operation is assumed to be done every year, by a medium tractor, considering 33 units per hour, a labor factor of 1.25, and a wage rate of $25/hour across the 3 years.

3 - Planting with in-furrow fertilizer and insecticide application

This operation is a 3-in-1 type: in the planting machine goes seeds, liquid phosphorus fertilizer, and liquid insecticide (Aztec®). The seeds used (V2TP or SmartStax®) depended on the treatment as well as the addition of the Aztec®. Because of this one-time application scenario for 3 different materials (the planting machine's operational efficiency), the difference in costs among treatments resided exclusively on the material costs and not on the field operations cost.

The Phosphorous fertilizer (P) is a common practice among treatments, and the one used in the budgets was a 10-34-0. Soils in Nebraska do not need Potassium (K) application, but a "starter fertilizer" with Phosphorous is recommended by the Budget Specialists to be placed close to the seed at planting time. This is not the case for Nitrogen (N), which explains the low amounts of this nutrient in a 10-34-0 formulation and also explains why fertigation is used later on with higher amounts of N.

The costs of the 10-34-0 fertilizer were $2.45 per gallon for 2020, used at 6 gallons per acre. The application rate for the seeds was the real ones used in the field experiments: 32.400 seeds per acre. V2TP and SmartStax® costs were obtained with the Nebraska Budgets Specialists from the University of Nebraska-Lincoln's official seed suppliers (not to be named) through phone calls. For V2TP in 2020, 2021, and 2022 the prices were $246.10/bag, $255.94/bag, and $266.18/bag, respectively. And for SmartStax® prices were $347.96/bag, $361.88/bag, and $376.36/bag. With each bag having 80.000 seeds, and an application rate of 32.400 seeds/acre, an average of 0.4 bags/acre was used.

The labor cost per hour used for planting was $25 across the 3 years, but the acres per hour were 10 (different than 33 for OI 1 and OI 2) and the labor factor was 1.2. The machine considered was a Planter for row crops (medium tractor), also 5 years old, with a list price of $83.593 for 2020. Diesel uses per hour was 2.58.

4- Herbicide application

The herbicide application after planting was assumed to be put in place every other year (50% of the time), using Glyphosate 5 with surfactant (32 ounces per acre at prices $15/gallon in 2020) and with the 21-0-0-24S additive (1.7 pounds per acre at prices $0.35/pound for 2020). As far as the tractor, the same assumptions made in OI 1 were made in OI 4.

5 - Post-emergence herbicide application

The herbicide Armazen Pro was considered 50% of the time (always sequentially to Glyphosate) at prices of $170/gallon for 2020, and an application rate of 14 ounces/acre. Spray cost was fixed at $7.00/acre assuming the farmer would hire this service.

6 - Fungicide application

Fungicide application would be needed 20% of the time (one application every five years), using Headline AMP at 10 ounces per acre and prices at $330/gallon in 2020. Spray service would be hired at $7.00/acre.

7 – Diesel irrigation and fertigation

The area assumed (130 acres) is a pivot section using diesel irrigation along with fertigation. The application rate for all fields and treatment was 9 inches of water regardless of the drought level of the year. The Center Pivot list price for 2020 was $75.000, 10 years old, making 1.8 acres per hour, with a labor factor of 0.083 (wage rate $25/hour), using 3.34 gallons of diesel per hour. The fertilizer used for fertigation was the 32-0-0 formulation (Nitrogen) with an application rate of 225 pounds of N/acre and prices for 2020 being $0.40/pound of N.

8 – Scouting

Scouting is a good practice recommended by UNL Specialists to be done every year. Its cost was $12 per acre in 2020.

9 – Grain drying

Dry grain is a field operation done every year but only in 10% of the area. It is an early harvest process conducted in a portion of the field before the ideal corn moisture is reached (with the grain still wet) to check the Combine machine. The harvested grains need to be dried, and so the costs depend on the yield (in this case, 10% of the total average yield). It is a hired service priced at $0.08/bushel in 2020.

10 – Harvesting

Harvesting is a different cost than Haul Grain because the budget was built in a way that there is a cost for the Combine operation per acre regardless of the yield obtained, whereas Haul Grain cost depends on the yield, which makes it a variable cost (VC). Although technically the combine’s efficiency depends on the yield (usually higher yields culminate in a slower combine) the budget does not capture this sensitivity.

The cost of the Combine includes labor cost (at $25/hour, 6.5 acres per hour, and a 1.1 labor factor), fuel cost (10.5 gallons of diesel per hour), and costs of repairs (assuming a list price for 2020 of $56.787 and a 5-year-old Combine).

11 – Cart and hauling

The cost for haul grain is considered a variable cost because it is based on yields. Prices used were \$0.11/bushel for 2020. The cart costs are also variable costs, with labor, fuel, and repairs priced in dollars per bushel (\$25/hour for labor, 1.1 as labor factor, 1.540 bushels per hour, and 3 gallons of diesel per hour).