GENETICALLY MODIFIED BT CORN REDUCES AFLATOXIN RISK IN US SOUTH: CROP INSURANCE ANALYSES

By

Wei-Ting Chiang

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ABSTRACT

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Aflatoxins produced by the fungi *Aspergillus flavus* and *Aspergillus parasiticus* are potent liver carcinogens. They commonly grow on corn in the southern United States. In 1996, transgenic Bt corn was planted in the US. Further, Bt corn contains vegetative insecticidal proteins (Vip) which were commercialized in 2011. The first study evaluated the effects of Bt corn, containing Bt corn, irrigation, and climate factors on aflatoxin risks in six southern US states from 2011-2016 by using corn growers' crop insurance claims as an analysis. The results showed that the higher adoption rate in Vip-containing Bt corn and total Bt corn, and irrigation reduced aflatoxin contamination in the southern US. In addition, the drought in July and wet September increased the risk of aflatoxin. The second study was aimed to understand the impacts of different Bt hybrids: Bt corn containing lepidopteran control, Bt corn containing corn rootworm control, and Bt corn containing both lepidopteran and corn rootworm control on aflatoxin- and drought-related insurance claims in the Southern US from 2003-2016. We found that Bt corn contains lepidopteran traits and was associated with lower aflatoxin risks. Moreover, the stacked hybrids that protect against both lepidopteran pests and corn rootworm had an additive effect on reducing aflatoxin risks. All three different Bt hybrids were associated with fewer drought risks, but Bt corn that targets corn rootworm had more effects on it. Overall, these results suggest that Vip-containing Bt corn has the potential to be used in reducing the aflatoxin damage. Bt corn and irrigation practice can also be the two strategies to reduce both aflatoxin and drought risks in commercial US corn fields.

This thesis is dedicated to my parents, Kuo-Chen Chiang and Hsiao-Fang Huang.
Thank you for their love, support, and patience.

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CHAPTER 1

Introduction

Aflatoxin is a secondary metabolite produced by the fungi *Aspergillus flavus* and *Aspergillus. parasiticus*, which is commonly found as contaminants in a variety of crops, like corn, tree nuts, or peanuts. Due to its adverse effects on both human and animal, aflatoxin has been classified as carcinogenic (Group 1) and potentially carcinogenic to humans (Group 2B) (IARC 1993). And more evidence has emerged in recent decades that aflatoxin exposure is also linked to acute liver failure (acute aflatoxicosis), child growth impairment, and immune system dysfunction (Khlangwiset et al. 2011; Saha Turna and Wu 2019; Strosnider et al. 2006). Aflatoxin risk is associated with high temperatures, dry conditions during the middle of the corn plants' growth stages, and heavy rainfall toward the end of the corn growing season (Williams et al. 2004). Therefore, the commonly high temperatures and frequent drought in the southeastern US lead to the presence of aflatoxin accumulation in corn fields (Bowen et al. 2014). Aflatoxins have been heavily regulated in the corn supply chain, and aflatoxin-related losses mainly affect the corn production market. Without proper strategies to control aflatoxins, as climate changes, these market losses are likely to increase over the next decade (Mitchell et al. 2016; Wu et al. 2011).

Corn has been the most widely produced crop in the United States, and more than 90 million acres have been planted as corn in 2020 (USDA ERS 2021). However, corn production in the southern US is vulnerable to aflatoxin contamination, especially because of the drought and heat stress during the corn growth period (Kebede et al. 2012). Previous studies have shown that the non-irrigated corn plants had higher aflatoxin contamination levels in corn kernels than irrigated corn plants (Jones et al. 1981; Kebede et al. 2012). The increase in drought stress is likely to increase the incidence of kernel damage through fungal infection. Therefore, strategies that can reduce aflatoxin or other production risk are needed, to lessen the corn growers' economic losses from the reduction in corn yields or price.

In 2013, nearly 48.7% of US corn was used for animal feed, and 30% was used for ethanol production (USDA ERS 2019). Recently, the portion of corn used in ethanol production has been raised to nearly 40% (USDA ERS 2021). Therefore, we not only care about aflatoxin for human consumption, but also for animal feed and for ethanol production. Since most of the ethanol in the US is produced from corn currently, mycotoxins in ethanol production or ethanol co-products have become one of the important concerns regarding the aflatoxin contamination in corn (Wu and Munkvold 2008).

The introduction of genetically modified (GM) plants, also known as genetically engineered plants, is helping farmers to reduce the production risk. The application of GM crops not only increases the farmer's profits by 68% on average but also increases the crop yields by 22% (Klümper and Qaim 2014). These indicate that farmers may have higher income and more profits by the application of GM crops. Therefore, many farmers have chosen to adopt GM plants rather than adopting conventional varieties in order to increase the benefits of agricultural practices, and also induce resource usage efficiency. GM crops, these kinds of technical crops have been applied in the fields for more than 20 years as well as introduced in markets. In the United States, there is nearly above 90% adoption rate for GM varieties in corn, cotton, and soybean (Lucht 2015). The U.S is the world's largest corn producer, and the majority of US corn used is for livestock feed (USDA ERS 2021).

The safety assessments of GM-related food and crops are ongoing. Numerous independent studies have not observed the relationship between adverse effects and the livestock that consume GM crops (Klümper and Qaim 2014). No significant differences have been found in the studies for the comparison of GM crops and non-GM crops in the nutrition profiles, performance, and feed digestibility (Van Eenennaam and Young 2014). However, the controversy over the GM food produced still remains, and the public concern of the GM food safety issue has not abated throughout the years. Collectively, there is still no strong evidence that can indicate the directly harmful effect of GM crops or food on human and animal health. Moreover, the development of GM crops is not affected by the controversies of the food security in GM food. The development of GM crops still expands every year with the cultivation.

Bt corn, a genetically modified corn that contains transgenes from the soil bacterium, *Bacillus thuringiensis* (Bt), was in the US in 1996. In the early years, Bt corn was introduced to control European corn borer and other lepidopteran pests in corn. And in 2003, another Bt corn with resistance to western corn rootworm (*Diabrotica virgifera*) was introduced to the corn fields (Hellmich and Hellmich 2012). Bt corn expresses insecticidal proteins from *Bacillus thuringiensis* to protect against insect pests. In 2011, nearly 65% of the corn was Bt corn (USDA NASS 2011). Meanwhile, Bt corn that specifically contains vegetative insecticidal proteins (Vip) was commercialized in the US in 2011. Vip-containing Bt corn has been used to control corn earworm (*Helicoverpa zea*) and fall armyworm (*Spodoptera frugiperda*), which are problematic in the Southern US (Flagel et al. 2018; Kaur et al. 2019). The adoption of the Bt corn can reduce the insect damage, thus, increasing the corn productivity and farmers' profits. Bt corn can make the crop production more efficient. Furthermore, corn growers can consider the combined use of improved genetics of corn resistance to insect pests and improved agronomy to prevent their economic losses from aflatoxin- or drought-related damage.

In the US, most of the farmers will buy crop insurance to protect against their losses of crops due to natural disasters or financial losses. The US government cooperates with private crop insurance companies to provide insurance to farmers. Where the United States Department of Agriculture's Risk Management Agency (USDA RMA) manages the Federal Crop Insurance Corporation to set rates and provides insurance coverage for much of the crop, further, private crop insurance companies do the marketing and sign the contract with farmers (USDA RMA 2016; Yu et al. 2020). Most common crop insurance policies include the one that insure yields and another one that insure farmers' revenue. When farmers identify and believe that there is a crop damage that appears in their crop fields, and which may cause adverse effects on their crop yield production or the value of the crop, they should contact their insurance provider and file a claim to require a visit to do the inspection (USDA RMA 2008; Yu et al. 2020). The loss adjuster will come and do the loss assessment, where procedures are described in a frequently updated Loss Adjustment Manual Standards Handbook in USDA RMA: https://www.rma.usda.gov/-/media/RMA/Handbooks/Loss-Adjustment-Standards---25000/Loss-Adjustment-Manual/2021-25010-1H-Loss-Adjustment-Standards-Handbook.ashx (USDA RMA 2008; Yu et al. 2020).

After the inspection, the loss adjuster will provide summary reports, which will be placed in the public domain at the USDA RMA website: http://www.rma.usda.gov/SummaryOfBusiness/CauseOfLoss. The reported causes of loss include drought, freeze, hail, heat, plant diseases, insects, wildlife, wind, excess moisture/rain/precipitation, and mycotoxin (Yu et al. 2020).

Based on the previous study from Yu et al. (2020), we discovered that the counties with higher adoption of Bt corn are associated with fewer aflatoxin-related insurance claims; however, the relationships between (a) aflatoxin and Vip-containing Bt corn, (b) aflatoxin and irrigation, (c) aflatoxin and drought risk and different Bt hybrids have remained unknown. To explore these unknown relationships, we devised the following research questions: (a) Does the Bt corn that contains Vip traits reduce the aflatoxin contamination in the Southern US where they have severe problems for corn armyworm and fall earworm?; (b) Can irrigation become one of the strategies in reducing aflatoxin risk?; (c) How do different Bt hybrids that target to control different insect pests affect the aflatoxin- and drought-related damage in US corn fields?

The first research is concerned with the relationship between Bt corn with or without Vip traits, total Bt corn, irrigation, and climate factors on the incidence of aflatoxin in the Southern US corn fields. With the assistance of my committee in this work, we first assumed that the corn fields planted with Bt corn with or without Vip traits and all Bt corn are associated with lower aflatoxin risks when controlling for the temperature, drought, and rainfall. Second, we assumed that the corn fields with the use of irrigation are also associated with a lower incidence of aflatoxin. Through the research, we discovered that counties in six southern US states- Arkansas, Kansas, Louisiana, Mississippi, Oklahoma, and Texas with a higher Bt corn adoption rate, Vip-containing Bt corn adoption rate, and irrigation had lower aflatoxin-related insurance claims from 2011-2016.

The second research focuses on different Bt corn hybrids effects, (a) hybrids containing lepidopteran control (b) hybrids containing corn rootworm control (c) hybrids containing both lepidopteran and corn rootworm control, on aflatoxin and drought risk in sixteen southern US states- Alabama, Arkansas, Georgia, Illinois, Iowa, Kansas, Kentucky, Louisiana, Mississippi, Missouri, Nebraska, North Carolina, Oklahoma, South Carolina, Tennessee, and Texas from 2003-2016. With the assistance of my committee and Dr. Munkvold in this study, we hypothesized that Bt corn containing corn rootworm traits is associated with lower aflatoxin- and drought-related insurance claims because of the protection in the root system. Moreover, we also included climate conditions that affect the growth of corn and aflatoxin, and irrigation to estimate the impact of different Bt hybrids on aflatoxin and drought risk. The results suggest that Bt corn with traits that target to control corn rootworm had obviously reduced drought-related insurance claims from 2003-2016. And, similar to the previous study in Yu et al. (2020), Bt corn with lepidopteran traits which can protect against corn borer, corn earworm, or fall armyworm was found to lower aflatoxin-related insurance claims. Moreover, the effects of irrigation on reducing aflatoxin and drought risk are important in different Bt hybrids.

Overall, my thesis study fills the knowledge gap of the effects of irrigation and Vip-containing Bt corn on aflatoxin production risks in the US corn fields. Additionally, we understand how those different Bt hybrids, which target different insect pests, have influenced the aflatoxin contamination and drought risks in US corn fields.

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CHAPTER 2

Vip-Containing Bt Corn and Irrigation Reduce Aflatoxin Risk in Southern US Corn Fields: An Analysis of Crop Insurance Claims and Environmental Factors

Abstract

Aflatoxins, liver carcinogens produced by the fungi *Aspergillus flavus* and *A. parasiticus*, are common contaminants of corn grown in hot, dry conditions and high insect populations, leading to perennial contamination problems in the southern United States. While transgenic Bt corn that produces its own insecticides has been planted in the United States since 1996, Bt corn that specifically contains vegetative insecticidal proteins (Vip) has only been available commercially since 2011. These Vip traits have improved control against corn earworm (*Helicoverpa zea*) and fall armyworm (*Spodoptera frugiperda*): two insect pests associated with *A. flavus* infection and subsequent aflatoxin contamination. We examined how corn growers' crop insurance claims for aflatoxin damage correlate with key environmental conditions and grower practices: drought, daily maximum temperatures, irrigation, Bt corn, and particularly Vip-containing Bt corn planting in six southern US states from 2011-2016. Bt corn, Vip-containing Bt corn planting and irrigation were all associated with lower aflatoxin risk in these six states. Additionally, a dry July and wet September increased aflatoxin risk, indicating the roles of drought in midsummer and excess moisture in late summer as additional risk factors for the developing corn plant. Overall, the region's declining water table together with climate change suggest that the region will face greater aflatoxin risks in the decades to come. Vip-containing Bt corn may play a role in reducing aflatoxin risk.

Key Words: transgenic corn, aflatoxins, drought, vegetative insecticidal proteins, economics

2.1 Introduction

In 1960, aflatoxins were first discovered when over 100,000 turkey poults in the United Kingdom died from consuming moldy peanut meal (Kensler et al. 2011). Since then, aflatoxin has been identified as the most potent naturally occurring human liver carcinogen. Additionally, it causes other adverse effects in humans and animals, ranging from acute liver failure to immune system dysfunction to growth impairment in children and other animal species (Khlangwiset et al. 2011; Strosnider et al. 2006; Wu et al. 2014).

Aflatoxins, a type of mycotoxins (fungal toxins), are produced by the fungi *Aspergillus flavus* and *A. parasiticus* in a variety of food and feed crops such as corn, peanuts, tree nuts (including almonds and pistachios), and cottonseed. Because Aspergilli are warm-weather fungi, aflatoxins are more common in these crops in tropical and subtropical regions of the world. In the United States, aflatoxins are perennially problems in corn and peanuts grown in the South (Mitchell et al. 2016). Other environmental factors that contribute to aflatoxin problems in corn are drought in midsummer months and insect pest damage on kernels (Yu et al. 2020).

Aflatoxins can cause various adverse health effects, hence over 100 nations worldwide have established maximum allowable levels of aflatoxins in food (Wu et al. 2013). These regulations are enforced at varying levels from nation to nation. In the US, the Food and Drug Administration (FDA) establishes and enforces action levels for aflatoxins in human food and various types of animal feed. Hence, the primary loss due to aflatoxins in the US is not through compromised human health, but through economic losses to *farmers*; whose crops are either rejected or bought at lower prices at grain elevators or handlers whenever aflatoxin levels exceed FDA action levels (Mitchell et al. 2016).

Therefore, it is important for farmers to consider strategies that can reduce aflatoxin risk, to lessen these associated economic losses. Several agronomic conditions have been identified over the last several decades as increasing the risk of aflatoxin contamination in corn. Aside from high temperatures, insect pests can increase the risk of fungal infection by damaging kernels and exposing the starches to the environment, and by vectoring fungal spores to different parts of the corn plant or other corn plants. Additionally, drought or heavy rainfall at key stages of corn plant development can increase plant stress, thus increasing susceptibility to fungal infection (Jones et al. 1981; Payne 1986). Hence, aflatoxin control strategies should focus on insect pest control and means to adapt corn to climate-related stresses.

Transgenic Bt corn, first commercialized in the United States in 1996, is genetically modified to produce insecticidal proteins that protect the corn plant from insect pest damage. By reducing insect pest damage, Bt corn protects yield (Fernandez-Cornejo and Wechsler 2012; Johnson et al. 2019; Xu et al. 2013). Early Bt corn events produced crystal (Cry) proteins that effectively controlled key pests such as the European corn borer and Southwestern corn borer, but had more limited efficacy against other kernel pests such as corn earworm and fall armyworm, which are prominent in Southern states (Wu 2004). In 2011, the first Bt events containing vegetative insecticidal proteins (Vip) in addition to Cry proteins were commercialized in the US. These Vip proteins provided improved pest control against corn earworm and fall armyworm, which are more common in the Southern US where aflatoxin events are more frequent.

In addition to the yield improvements that Bt corn offers, its protection from insect pests also confers another important benefit alluded to above, from the perspective of human and animal health (and economic savings): mycotoxin control. It was first discovered in the late 1990s that Bt corn had lower levels of the mycotoxin *fumonisin* compared with non-Bt isolines (Munkvold et al. 1999). Subsequent field studies in different parts of the world showed consistent reductions in *fumonisin* levels in Bt corn compared with non-Bt isolines (De La Campa et al. 2005; Hammond et al. 2004).

Until recently, the evidence that Bt corn reduces aflatoxin risk was less clear in field studies. At least in part, this may be because aflatoxins in corn are produced by the fungus *Aspergillus flavus*, which is a warm-weather fungus and hence is more common in the Southern US; and earlier Bt corn events had limited protection against the major insect pests in the South (corn earworm (*Helicoverpa zea*) and fall armyworm (*Spodoptera frugiperda*)). However, Pruter et al. (2019) showed that Bt corn, including hybrids with crystal and Vip proteins, showed lower aflatoxin incidence than non-Bt hybrids in field plots in Texas; and that the association of insect damage and aflatoxin contamination was stronger in water-limited conditions. Yu et al. (2020) further showed that in commercial US corn fields, where Bt corn was planted, there were significantly fewer aflatoxin-related crop insurance claims; even when controlling for temperature and drought. If Bt corn can become one tool in reducing aflatoxin risk, then there could be substantial benefits in terms of reduced economic losses to corn growers in the US, as well as human and animal health benefits in other parts of the world where aflatoxins are common contaminants in food and feed. Yu et al. (2020) estimated a benefit to corn growers of $120-167 million annually from reduced aflatoxin costs in 16 states encompassing the major corn-planting states east of the Rocky Mountains.

We take this analysis further by specifically evaluating the evidence for Vip-containing Bt corn in reducing aflatoxins, as it should have increased efficacy in controlling the pests that are specifically associated with aflatoxins. One vegetative insecticidal protein, Vip3A, has been introduced into Bt corn to provide improved protection against corn earworm and fall armyworm. We focus on six Southern states, where corn earworm and fall armyworm are common pests in corn and should be susceptible to Vip-containing Bt corn. Additionally, we account for irrigation practices by corn growers in these six states, which is another important tool in reducing drought stress in corn plants; thereby reducing the risk of *A. flavus* infection and aflatoxin accumulation.

2.2 Materials and methods

Our current analysis spans 2011-2016, which accounts for the first six years of Vip-containing Bt corn events (abbreviated to Vip for the remainder of this manuscript) being planted in the US. **Figure. 2.1** shows the acreage of Vip adoption rates from 2011–2016 (created in ArcMap 10.7.1, https://desktop.arcgis.com/en/arcmap), in six corn-planting states in the US South: Arkansas, Kansas, Louisiana, Mississippi, Oklahoma, and Texas. Vip corn planting data was obtained from Kynetec Ltd. As can be seen, Vip adoption rates have increased over time.

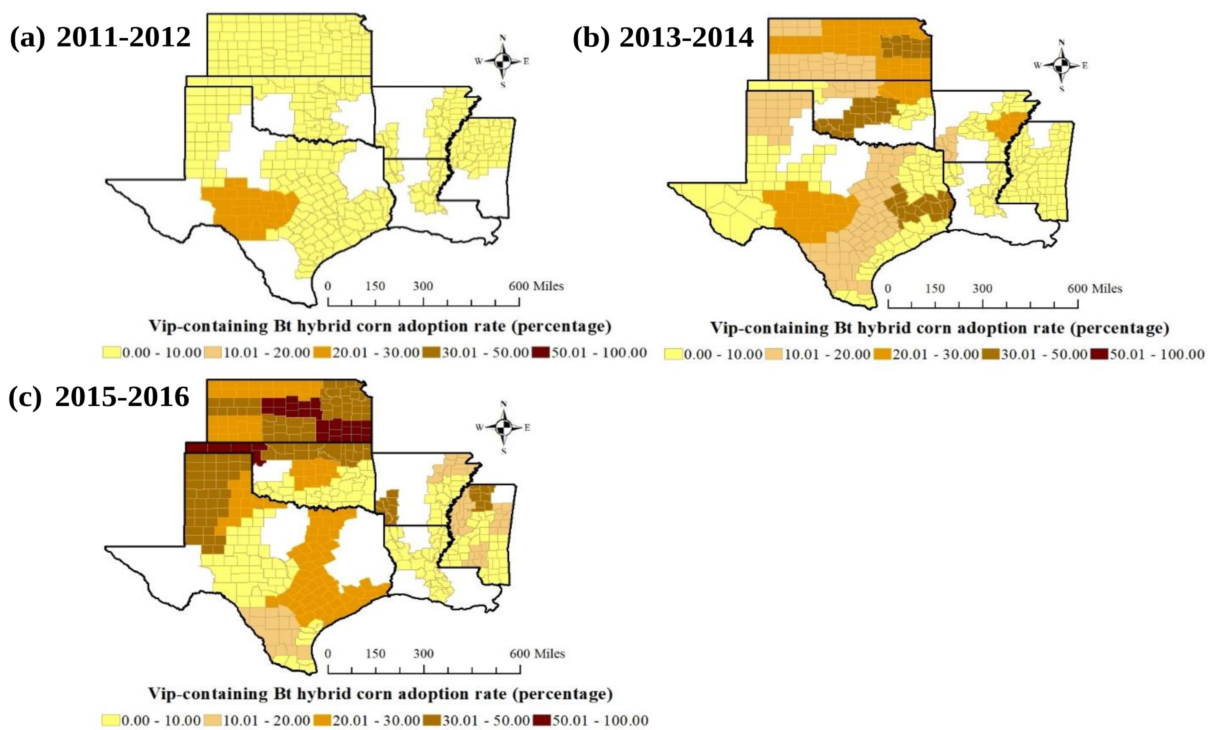

Figure. 2.1 Vip corn adoption rates in: (a) 2011-2012, (b) 2013-2014, (c) 2015-2016; averaged within crop reporting districts in six selected US corn-planting states. The white portions in the six-state area were excluded from analysis because data on corn planting were missing over some or all of the study period 2011-2016.

This general expansion in use over the time period 2011-2016 may be partly due to increased availability of corn hybrids that include the Vip protein, and may also be partly due to typical trends of technological adoption among farmers when new technologies are recognized as beneficial, first taking hold in central production locations (the Midwest for corn) before diffusing out (Griliches 1960). Aflatoxins occur only when weather conditions favorable to fungal infection and aflatoxin production from the fungus occur over a crop disposed to infection, where insect damage is one route through which invasion can take place (Yu et al. 2020). However, farmers have historically been more concerned about the direct yield losses caused by insect damage from corn earworm and fall armyworm, rather than by aflatoxins.

Figure 2.2 shows a different time average of aflatoxin-related insurance claims counts which are normalized by the number of total insured policies on corn in 6 corn-planting states for 2011-2016. We can see that the counties with less aflatoxin incidence are consistent with the higher Vip-containing adoption rate in Figure 2.1.

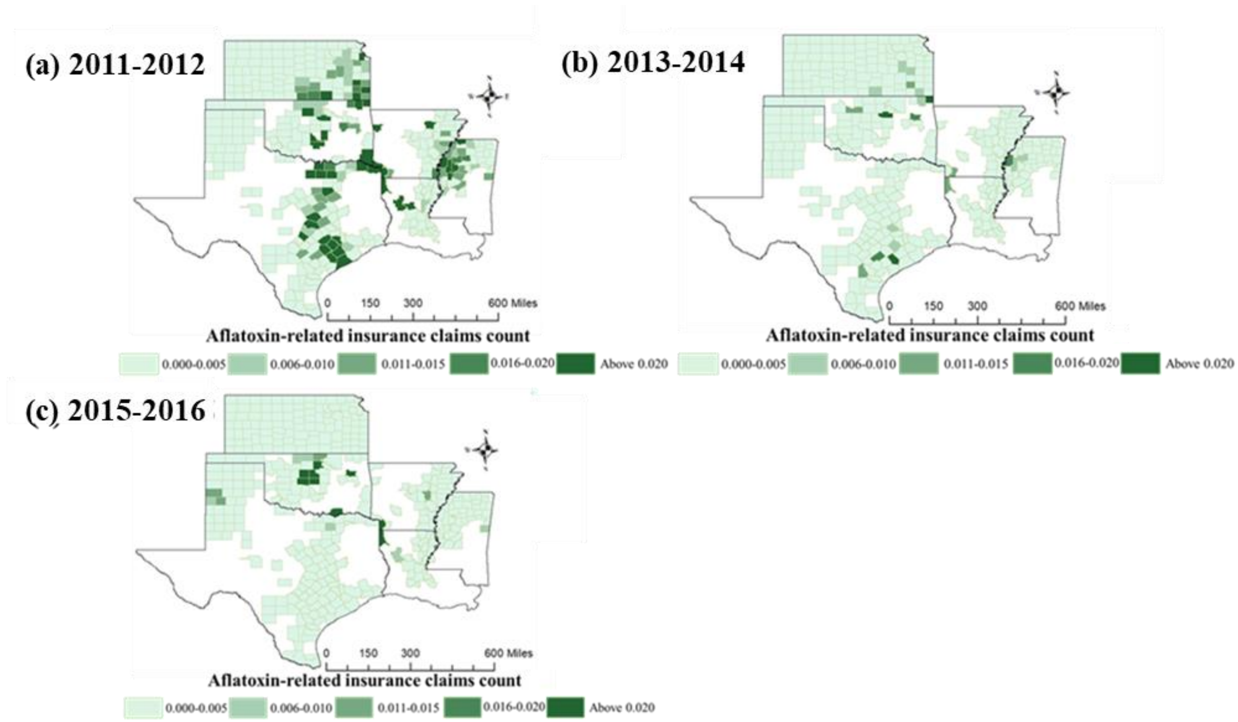

Figure 2.2 Aflatoxin-related insurance claims counts in: (a) 2011-2012, (b) 2013-2014, (c) 2015-2016; averaged in six selected US corn-planting states. The white portions in the six-state area were excluded from analysis because data on total insured policies of corn were missing over some or all of the study period 2011-2016.

Figure. 2.3 shows irrigation levels in each county in the six-state region in 2016, as represented by the ratio of irrigated land acres in the county over harvested cropland acres in that county. Irrigation levels in a county have changed slowly over time during recent decades because the investment required to irrigate is large (Edwards and Smith 2018; Ge et al. 2020). Furthermore, such investments will only occur when water for irrigation is both i) available from over-ground or under-ground sources and ii) needed given land suitable for cropping.

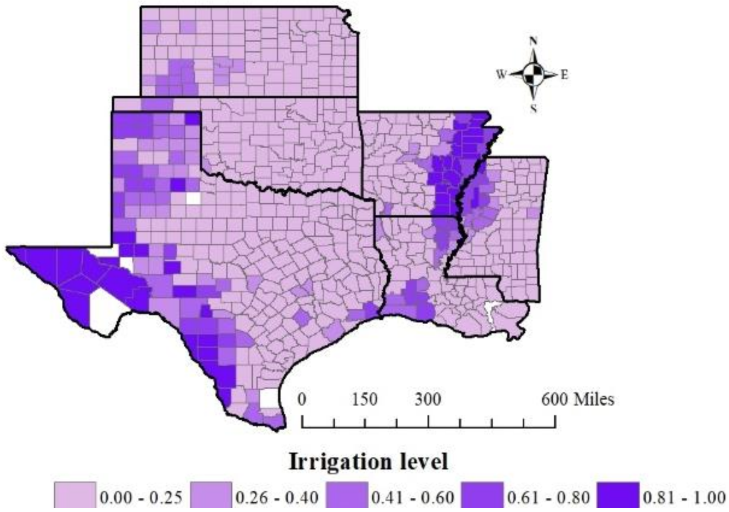

Figure. 2.3 Irrigation in 2016 by each county in six selected corn-planting states. The white portions in the six-state area were excluded from analysis. Source: US Census of Agriculture, 2012 and 2017.

In the current study, we estimated the risk of aflatoxin-related insurance claims in these six Southern states as a function of the following grower and environmental variables: Bt corn planting, both with or without Vip traits; irrigation; drought indices for key corn planting months; and maximum daily temperatures during key months of the corn growing season. To measure the risk of aflatoxin-related insurance claims, we used crop insurance data. The vast majority of US corn growers now purchase crop insurance, whose premiums and operation costs are heavily subsidized by the United States government. Since the middle 1990s, crop insurance has been administered by the United States Department of Agriculture Risk Management Agency (USDA RMA) who determine contract form and set the premium rates. Private companies market these contracts, administer claims, and underwrite some of the contracts (Government Accountability Office 2005). County-level aggregated insurance data such as premium and indemnity claims are publicly available from USDA RMA webpages.

2.2.1 Data sources

Aflatoxin-related insurance claims data were collected from the USDA Risk Management Agency (RMA) Cause of Loss (COL) database. Crop insurance typically covers production losses due to natural events, including drought, wind, excessive moisture, heat, cold, frost, insects, plant diseases, wildlife damage, wind, and mycotoxins [aflatoxins]. Significant reductions in prices may also be covered depending on the insurance contract chosen. Specifically, we collected the claims as either 0 or 1 in a given county and year, indicating whether there were claims made by a corn grower (1) or not (0). Because aflatoxins are the only mycotoxins that have been regulated by action levels by the FDA, we assumed that where the indemnified cause of loss description is ascribed to mycotoxins, the specific cause of concern was aflatoxins (the label in USDA RMA is for "mycotoxins [aflatoxins]"). We considered the 2011-2016 time window, beginning when Vip proteins were commercialized and ending in the last year for which we had corn seed purchases data. In order to exclude the possibility that the insurance claims were made for the losses during the corn storage stage, we collected insurance claims only for the months June to October inclusive. Bt corn events, differentiated for those with or without Vip proteins, were obtained from Kynetec Ltd – an agricultural survey and market analysis company – at the crop reporting district (CRD) level where each state is divided into approximately nine CRD.

We obtained irrigated land acres and harvested cropland acres for each corn-growing county in the six-states from the US Census of Agriculture, available for the years 2006, 2011 and 2016 (reported in 2007, 2012 and 2017 Census, respectively. https://www.nass.usda.gov/AgCensus/). To obtain the irrigation ratio, we linearly interpolated the irrigated acres and harvested cropland acres increase (or decrease, where appropriate) between the two nearest Census years. Then the irrigation ratio is calculated as irrigated land acres divided by harvested cropland acres.

Additionally, we collected Palmer's Z index data from 2011 to 2016, June through

September from the US National Oceanic and Atmospheric Administration (NOAA); these months encompass the key growth stages of the corn plant in which drought or heavy rainfall may affect fungal infection and aflatoxin production risks. Palmer's Z can take values ranging from -7 to 7; where 0 represents normal moisture levels for the region compared with historical trends, -3 is very dry, and 3 is very wet. These Palmer's Z values are made available by NOAA at the climate zone level of aggregation. Climate zones correspond to approximately nine counties and are broadly consistent with CRD boundaries. From NOAA, we also gathered daily maximum temperatures from 2011 to 2016, May through August in each year inclusive. We aggregated weather station level data to the county that the weather station is located in, and calculated the proportions of days that had a daily maximum temperature in the 32-40°C range. According to previous research, this temperature range is within the bounds of the key range for aflatoxin production (Yu et al., 2020). Summary statistics and data sources are listed in **Table 2.1**.

Table 2.1 Summary statistics and data sources for models of aflatoxin-related insurance claims as a function of Bt and Vip corn planting, irrigation, drought and rainfall, and temperature.

Variable	Data Source	Unit of Analysis	Representation	Mean	Std. Dev.
Aflatoxin-related insurance claims	USDA RMA	County	$y_{i,t} \in \{0,1\}$	0.126	0.332
Total Bt corn adoption rate	Kynetec	Crop District	$U_{i,t} \in [0,100]$	78.147	18.125
Bt (non-Vip) adoption rate	Kynetec	Crop District	$B_{i,t} \in [0,100]$	63.012	20.545
Vip adoption rate	Kynetec	Crop District	$V_{i,t} \in [0,100]$	15.135	18.278
Ratio of irrigated land acres to harvested cropland acres	Census of Agriculture	County	$I_{i,t} \in [0,1]$	0.230	0.277
Corn insured acres	USDA	County	$A_{i,t}$	23,701	29,092
[§]Palmer's Z for select months $m \in \{6,7,8,9\}$	NOAA	Climate District	$Z_{i,t}^{6} \in [-7,7]$	-0.579	2.058
			$Z_{i,t}^{7} \in [-7,7]$	-0.190	2.229
			$Z_{i,t}^{8} \in [-7,7]$	0.171	2.289
			$Z_{i,t}^{9} \in [-7,7]$	-0.514	1.564

Table 2.1 (cont'd)

Variable	Data Source	Unit of Analysis	Representation	Mean	Std. Dev.
§Ratio of days with maximum temperatures between 32-40°C to days in month for select months $m \in \{5,6,7,8\}$	NOAA	Weather station	$T_{i,t}^{5}$	0.149	0.175
			$T_{i,t}^{6}$	0.568	0.220
			$T_{i,t}^{7}$	0.700	0.211
			$T_{i,t}^{8}$	0.642	0.204

§Month coding is given by May=5, June=6, July=7, August=8, September=9

2.2.2 Regression model to estimate impact of risk factors on aflatoxin-related insurance claims

Annual aflatoxin-related insurance claims data are reported as only two values, either 0 or 1, which indicates whether insurance claims were made by a corn grower (1) or not (0) in a particular county and year. The Probit regression is a model that has been used to perform the regression for binary dependent variables which only take on values 0 or 1 at each observation. In our case, the event outcomes are corn plantings with aflatoxin claim outcomes (0 or 1), while the conditioning is on weather and technology. To fit our data, we chose the Probit regression in the Stata statistical analysis package and the regression was estimated with acreage offset in order to normalize for corn acres planted.

To estimate the predicted probability of aflatoxin insurance claims when conditional on the independent variables, we assumed the model be formed as:

$$\text{Prob}(y_{i,t} = 1 \mid X) = \Phi(X'\beta) \tag{1}$$

Where $y_{i,t}$ represents the insurance claims, which are either 0 or 1 in county *i* in year *t*, and $X_{i,t}$ as the explanatory variable vector in the given county and year. β is the coefficient vector, which is typically estimated by maximum likelihood methods. And $\Phi(\cdot)$ denotes the cumulative density function of standard normal distribution.

Thus, when bringing data to the model we posit two alternative specifications:

$$\begin{aligned}&(2a)\quad X'\beta = \beta_0 + \ln(A_{i,t}) + \beta_B B_{i,t} + \beta_V V_{i,t} + \beta_I I_{i,t} + \sum\nolimits_{m\in\{6,7,8,9\}} \beta_Z^m Z_{i.t}^m + \sum\nolimits_{m\in\{5,6,7,8\}} \beta_T^m T_{i.t}^m + \varepsilon_{i,t};\\ &(2b)\quad X'\beta = \beta_0 + \ln(A_{i,t}) + \beta_U U_{i,t} + \beta_I I_{i,t} + \sum\nolimits_{m\in\{6,7,8,9\}} \beta_Z^m Z_{i.t}^m + \sum\nolimits_{m\in\{5,6,7,8\}} \beta_T^m T_{i.t}^m + \varepsilon_{i,t};\end{aligned} \tag{2}$$

where acreage $A_{i,t}$ as the insured acres are included to recognize and offset scale effects whereby the responses of the probability of claims in each county should scale in direct proportion to the number of corn acres insured in the county. The other variables are as described in Table 1. Specification (2a) distinguishes between Bt corn with and without the Vip trait while (2b) does not. Our maintained hypotheses are:

$$\begin{aligned}&\text{H1:}\quad \beta_B < 0,\ \beta_V < 0 \text{ for } (2a) \text{ and } \beta_U < 0 \text{ for } (2b);\\ &\text{H2:}\quad \beta_I < 0 \text{ for } (2a) \text{ and } (2b).\end{aligned} \tag{3}$$

The first hypothesis asserts that Bt corn without Vip (β_B), Bt corn with Vip (β_V), and all Bt corn regardless of Vip (β_U) decrease the number of aflatoxin-related insurance claims. The second hypothesis asserts that a more irrigated county is also likely to have lower aflatoxin-related insurance claims.

The model is estimated by maximum likelihood estimation methods, and the parameter vector of interest is found from solving the joint log-likelihood maximization problem, i.e., by assuming that data outcome probabilities are independent, when conditioned on X, choosing β to maximize log likelihood that is arrived at from logging the product of (1) across all data, i.e., $y_{i,t} = 0$ and $y_{i,t} = 1$, and then choosing parameters to maximize the likelihood:

$$\begin{aligned}\hat{\beta} &= \arg\max_\beta \ln L(\beta; y, X)\\ &= \arg\max_\beta \sum\nolimits_{i=1}^{n}\left[y_{i,t}\ln[\Phi(X'_{i,t}\beta)] + (1-y_{i,t})\ln[1-\Phi(X'_{i,t}\beta)]\right].\end{aligned} \tag{4}$$

2.3 Results

The effects of drought vs. moisture (Palmer Z indices) were significant and negative in July but significant and positive in September. Although the effects were positive in August, for each model they were not statistically significant. These indicate that drought in July, as well as rainfall in September, increase the risk of aflatoxin contamination in corn fields. Additionally, high temperatures in June and July are correlated with increased aflatoxin risk.

During the six-year period 2011-2016, Bt corn was planted on about 78.1% of the acres devoted to corn in these six Southern states. More specifically, 15.1% of the acreage was devoted to Bt corn that contained Vip traits while 63.0% was devoted to Bt corn that did not contain Vip traits on average.

Table 2.2 provides the regression results for equations (2a) and (2b). Negative coefficient values indicate that the variable in question is associated with reduced risk of aflatoxin-related insurance claims in the period from 2011-2016.

Table 2.2 Regression results for Probit Regression

Variables	2(a)	2(b)
Agronomic variables		
Non-Vip Bt corn adoption rate	-0.004	
	(-1.23)	
Vip Bt corn adoption rate	-0.033***	
	(-7.40)	
Bt corn adoption rate		-0.011***
		(-3.86)
Irrigated ratio	-1.832***	-1.672***
	(-10.54)	(-9.66)
Palmer's Z indices		
June	0.050	0.036
	(1.48)	(1.11)
July	-0.151***	-0.208***
	(-4.96)	(-7.30)
August	0.015	0.001

Table 2.2 (cont'd)

Variables	2(a)	2(b)
Palmer's Z indices		
	(0.58)	(0.02)
September	0.049*	0.019
	(1.65)	(0.63)
Proportion of days with maximum temperature between 32-40°C		
May	-0.006	0.419
	(-0.02)	(1.36)
June	2.048***	1.977***
	(7.68)	(7.46)
July	0.916***	0.712**
	(3.01)	(2.36)
August	-1.457***	-0.902***
	(-4.67)	(-3.01)
Constant	-10.914***	-11.054***
	(-33.15)	(-33.88)
No. of observations	1,807	1,807
Log-likelihood	-845.26	-865.16
Chi-square	392.89	367.79
Prob > chi2	0.00	0.00

*Notes: z-statistics in parentheses. *** p<0.01, ** p<0.05, * p<0.1*

Column (2a) in Table 2 shows that, although Bt corn not containing Vip traits has a negative effect on aflatoxin-related insurance claims, the variable's coefficient was not statistically significant. In contrast, Vip-containing Bt corn did appear to significantly reduce aflatoxin risk. This is as expected, given the evolving insect resistance to non-Vip Bt and the improved efficacy of Vip corn against pests that are particularly problematic in the US South: corn earworm and fall armyworm (Flagel et al., 2018; Kaur et al., 2019). Similarly, in column (2b), the total Bt corn adoption rate has a significant and negative sign indicating that total Bt corn is statistically associated with fewer aflatoxin-related insurance claims; possibly because Vip Bt traits are increasingly effective against the insect pests that predispose corn to aflatoxin damage. In both specifications, irrigation also significantly reduces aflatoxin risk. Thus, we have evidence in favor of hypotheses H1 for (2b) and H2.

A comparison with findings in Yu et al. (2020) is in order. That study used similar data sets but covered a broader range of states and did not seek to account for irrigation, which is not a common corn production practice east of Nebraska. The study found that while Bt corn not containing Vip traits was significantly associated with low insurance claims for aflatoxin, Vip-containing Bt corn did not affect aflatoxin-related insurance claims. However, in our research the presence of Vip-containing Bt corn planting and an increase in irrigation are both associated with low aflatoxin risk.

2.4 Discussion

Bt corn with Vip traits have been planted in the US with intent to better protect the crop against corn earworm and fall armyworm. In addition to reducing yield losses, the technology could reduce quality losses through reducing aflatoxin infestations. Our study provides evidence in favor of this possibility: namely, where Vip-containing Bt corn was planted in six Southern US states that typically have aflatoxin risks in corn from the years 2011-2016, there were significantly fewer aflatoxin-related insurance claims. This held true even when controlling for temperature, drought/rainfall, and irrigation. On the last: irrigation was also associated with significantly fewer aflatoxin-related insurance claims when controlling for drought/rainfall. Additional factors that we showed to increase the risk of aflatoxin are high temperatures in June and July, and drought in June and rainfall in September. These last are consistent with the findings in Yu et al. (2020), which had covered a broader range of states, but did not account for irrigation and did not differentiate between different Bt corn traits.

Although Bt corn, Vip-containing Bt corn planting and irrigation could lower the incidence of aflatoxin-related insurance claims, these are but three strategies to reduce aflatoxin risk in corn.

Application of biocontrol agents, good agricultural practices, and appropriate storage and transportation conditions for corn after harvest are other important strategies to be adopted along the corn supply chain to reduce aflatoxin accumulation (Khlangwiset and Wu 2010). However, the benefit of aflatoxin reduction shown by irrigation may be important for future corn planting in the US under changing climatic conditions and altered risk of aflatoxin.

We see several policy implications to our analysis. The 2018 United States National Climate Assessment for the Southern Great Plains has stated (Kloesel et al. 2018):

> "Average annual precipitation projections suggest small changes in the region, with slightly wetter winters, particularly in the north of the region, and drier summers (Easterling et al. 2017). However, the frequency and intensity of heavy precipitation are anticipated to continue to increase, particularly under higher scenarios and later in the century (Easterling et al. 2017). The expected increase of precipitation intensity implies fewer soaking rains and more time to dry out between events, with an attendant increase in soil moisture stress. Studies that have attempted to simulate the consequences of future precipitation patterns consistently project less future soil moisture, with future conditions possibly drier than anything experienced by the region during at least the past 1,000 years (Cook et al. 2015)."

Environmental conditions will likely become more conducive to aflatoxin problems in US corn in the future. Precipitation extremes, both flooding and drought, are anticipated where rising temperatures will exacerbate water shortfalls through evapotranspiration. Corn yields in the United States Midwest and Great Plains regions are known to be very sensitive to drought conditions (Schlenker and Roberts 2009) where less water intensive crops with lower input requirements are likely to have a comparative advantage under anticipated future climate regimes (Arora et al. 2020; Rising and Devineni 2020). Corn crop adaptation strategies, including changing variety and planting date, are projected (Baum et al. 2020) or are already in effect (Kucharik et al. 2006). Little is known about how these strategies will affect corn quality attributes. At the same time, the massive Ogallala Aquifer that supports much of the irrigation observed in Figure 2.3 will deplete over the coming decades such that cropping cannot be supported in many parts of the region (Deines et al. 2020). All else fixed, a warmer, drier climate when unshielded by irrigation will likely depress corn yields and increase yield variability (Kucharik et al. 2020; Kukal and Irmak 2018; Leng 2017). We show that these conditions will also lead to an aflatoxin-induced decrease in corn quality, placing further stress on the crop in the six-state region under consideration. The effect will occur even at given irrigation rates, but will be strengthened to the extent that climate change increases demands on aquifer resources and limits its availability for managing water stress. Much of the world's crop agriculture is supported by depleting groundwater sources (Richey et al. 2015). Further research on implications for crop quality is warranted.

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CHAPTER 3

Adoption of Transgenic, Insect-Protected Corn Reduces Aflatoxin- and Drought-Related Insurance Claims

3.1 Introduction

Since 1996, transgenic Bt corn, a corn contains transgenes from the soil bacterium, *Bacillus thuringiensis* (Bt), has evolved from containing one plant-incorporated protectant per hybrid to multiple stacked and pyramided traits in the same hybrid. Early Bt events protected against corn borers such as *Ostrinia nubilalis* (European corn borer, ECB), with limited protection against other lepidopteran pests that feed on kernels. In 2003, the first events protecting against *Diabrotica virgifera* (western corn rootworm, CRW) were planted, and later years saw the stacking of traits to protect against multiple insect pests, as well as to confer herbicide and drought tolerance. We determined if these transgenic traits protected against aflatoxin and drought risk by analyzing crop insurance claims made by United States corn growers from 2003-2016. Hybrids containing lepidopteran protection alone or stacked with CRW traits protected against aflatoxin risk, with a greater effect in stacked events. Both lepidopteran and CRW traits showed reduced drought damage, with the strongest effect in CRW-protected corn: likely because healthier root systems improved water utilization.

Bt corn contains crystal (Cry) proteins or vegetative insecticidal proteins (Vip) that are toxic to insect pests feeding on the corn kernels or roots (or both). Aside from protecting against the productivity losses caused by insect damage and "lodging" (inadequate root system causing corn plants to collapse), transgenic insect protection has important secondary benefits. Reducing kernel damage also reduces the risk that the corn will become infected by fungi that produce toxins (mycotoxins). Since the late 1990s, it was known that Bt corn reduces the risk of contamination by fumonisins, mycotoxins produced by the fungi *Fusarium verticillioides* and *F. proliferatum* on corn (Munkvold et al. 1999). More recently, Bt corn planting was found to significantly reduce the risk of aflatoxin-related insurance claims as well (Yu et al. 2020), with a particular benefit for hybrids containing Vip events that add protection against *Helicoverpa zea* (corn earworm) and *Spodoptera frugiperda* (fall armyworm). This may be an important finding that extends beyond economic impacts to animal and human health impacts, as aflatoxin is the most toxic and carcinogenic of the known mycotoxins. Produced by the fungi *Aspergillus flavus* and *A. parasiticus*, aflatoxin is a common contaminant of corn and nuts grown in warm climates worldwide. It causes liver cancer (Kensler et al. 2011), and is associated with immunotoxicity and growth impairment in humans and animals (Khlangwiset et al. 2011; Wu et al. 2014).

To examine how the different transgenes affect aflatoxin and drought risks to corn growers, we conducted two binary response Probit regressions with aflatoxin- and drought-related insurance claims as outcome variables, and transgenes protecting against corn borer, corn rootworm, or both as the primary independent variables; with confounders and co-factors included of irrigation practices, Palmer Z indices in key corn growing months (a measure of soil drought or moisture), and maximum daily temperatures above 32°C in key growing months. We conducted this analysis for insurance claims made in the years 2003-2016, in sixteen major corn-producing states. Past studies have shown that irrigation plays an important role in reducing both aflatoxin- and drought-related stresses in the field (Khlangwiset and Wu 2010; Payne 1986). Additionally, soil moisture and maximum daily temperatures are important risk factors for aflatoxin (Yu et al. 2020).

Figure. 3.1 shows the average adoption rate of Bt hybrids that contain different traits in the sixteen-state region in 2006, 2011, and 2016. The adoption rate of the stacked hybrids was increasing over time, and Bt corn that only contains rootworm traits were rarely planted by corn growers among these sixteen states.

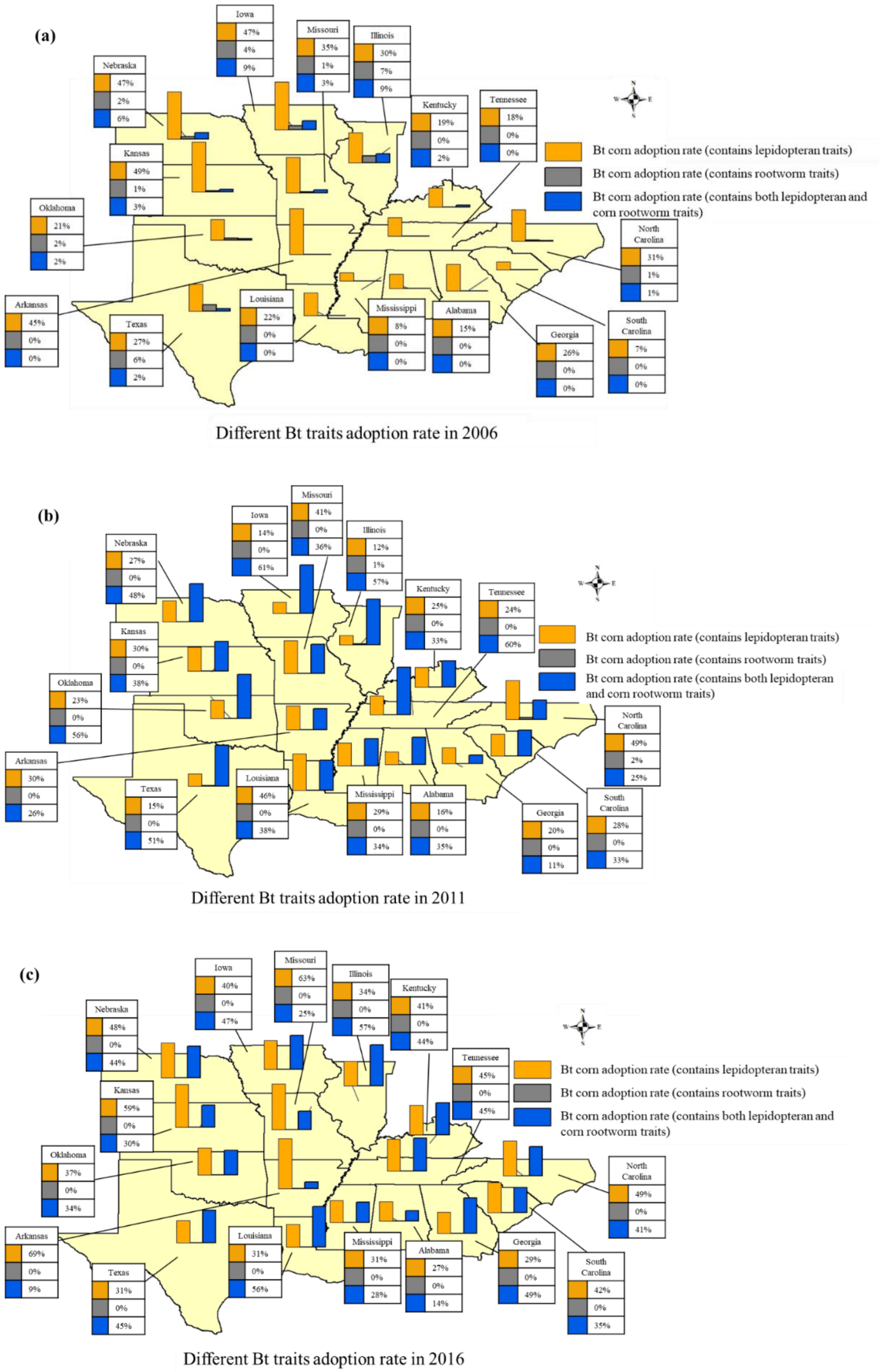

Figure. 3.1 Different Bt traits adoption rate in: (a) 2006, (b) 2011, (c) 2016

3.2 Materials and methods

The crop insurance data are public domain data from the United States Department of Agriculture (USDA) Risk Management Agency, which collects and reports crop insurance data for multiple different causes of crop loss on all the major crops grown in the United States. See Perry et al. (2020) for use of these data to understand climate change perils. Crop insurance is heavily subsidized so that the majority of corn acres have been insured since the middle 1990s and over the past decade above 85% of corn planted acres have been insured across the United States, https://www.rma.usda.gov/SummaryOfBusiness. Data on use of different transgenes at the crop reporting district level were obtained from Kynetec, Ltd., an agricultural survey firm that surveys about 4,500 corn farm operations annually about their seed and plant protection choices. Irrigation data was obtained from the Agriculture of the National Agricultural Statistical Survey conducted by the USDA. To obtain the irrigation ratio, we assumed that the irrigated and harvested acres increase (or decrease, where appropriate) linearly by year. Then the irrigation ratio is calculated as irrigated land acres divided by harvested corn acres. Data on historical Palmer Z indices by climate district and maximum daily temperatures by weather station were obtained from the US National Oceanic and Atmospheric Administration (NOAA). Summary statistics and data sources are listed in **Table 3.1**.

Table 3.1 Summary statistics and data sources for model of aflatoxin- and drought-related insurance claims as a function of different insect resistance traits, planting, irrigation, drought and rainfall, and temperature.

Variable	Data Source	Unit of Analysis	Representation	Mean	Std. Dev.
Aflatoxin-related insurance claims	USDA RMA	County	$y_{1,i,t} \in \{0,1\}$	0.062	0.240
Drought-related insurance claims	USDA RMA	County	$y_{2,i,t} \in \{0,1\}$	0.623	0.485

Table 3.1 (cont'd)

Variable	Data Source	Unit of Analysis	Representation	Mean	Std. Dev.
Bt corn adoption rate (contains both lepidopteran and corn rootworm traits)	Kynetec	Crop Reporting District	$B_{i,t} \in [0,100]$	24.662	23.439
Bt corn adoption rate (only lepidopteran traits)	Kynetec	Crop Reporting District	$C_{i,t} \in [0,100]$	32.671	19.855
Bt corn adoption rate (only rootworm traits)	Kynetec	Crop Reporting District	$R_{i,t} \in [0,100]$	0.690	2.470
Ratio of irrigated land acres to harvested cropland acres	Census of Agriculture	County	$I_{i,t} \in [0,1]$	0.148	0.225
Corn insured acres	USDA	County	$A_{i,t}$	40,413	53,210
[§]Palmer's Z for select months $m \in M = \{6,7,8,9\}$	NOAA	Climate District	$Z_{i,t}^{6} \in [-7,7]$	0.243	2.338
			$Z_{i,t}^{7} \in [-7,7]$	0.260	2.353
			$Z_{i,t}^{8} \in [-7,7]$	0.376	2.272
			$Z_{i,t}^{9} \in [-7,7]$	0.077	2.143
[§]Ratio of days with maximum temperatures above 32°C to days in month for select months $m \in M = \{5,6,7,8\}$	NOAA	Weather station	$T_{i,t}^{5}$	0.090	0.140
			$T_{i,t}^{6}$	0.361	0.279
			$T_{i,t}^{7}$	0.511	0.298
			$T_{i,t}^{8}$	0.465	0.303

[§]Month coding is given by May=5, June=6, July=7, August=8, September=9

Annual aflatoxin- or drought-related insurance claims data are reported as only two values (0 or 1), indicating the claim was made by a corn grower (1) or not (0). The Probit regression has been used as a model to perform the regression for binary dependent variables which only take on values 0 or 1 at each observation. Thus, to fit our data we chose the Probit regression in the Stata statistical analysis package. The regression was estimated with acreage offset in order to normalize for acres insured.

With explanatory data for county i in year t as $X_{i,t}$ and corresponding claims as $y_{k,i,t}, k \in \{1,2\}$, which are either 0 or 1. We assumed the model be formed as:

$$\text{Prob}(y_{k,i,t} = 1 | X) = \Phi(X'\beta)$$

where $\Phi(\cdot)$ is the standard normal cumulative density function, X' represents the transposed matrix of explanatory variables with particular (county, year) realization $X_{i,t}$ and β is the coefficient vector to be estimated. The model will calculate a predicted probability of insurance claims based on our independent variables. Thus:

$$X'\beta = \beta_0 + \ln(A_{i,t}) + \beta_B B_{i,t} + \beta_C C_{i,t} + \beta_R R_{i,t} + \beta_I I_{i,t} + \sum_{m \in M} (\beta_Z^m Z_{i,t}^m + \beta_T^m T_{i,t}^m),$$

where corn insured acreage $A_{i,t}$ is included to recognize and normalize for (i.e., offset) scale effects. The model is estimated by maximum likelihood methods, and the parameter vector of interest is found from solving the joint log-likelihood maximization problem:

$$\begin{aligned}\hat{\beta} &= \arg\max_{\beta} \ln L(\beta; y, X) \\ &= \arg\max_{\beta} \sum_{i=1}^{n} \left[y_{k,i,t} \ln[\Phi(X'_{i,t}\beta)] + (1 - y_{k,i,t}) \ln[1 - \Phi(X'_{i,t}\beta)] \right].\end{aligned}$$

3.3 Results and Discussion

Table 3.2 shows the estimated results. Negative coefficient values indicate that the variable in question is associated with reduced risk of either aflatoxin- or drought-related insurance claims in the period from 2003-2016.

Table 3.2 Regression results for Probit model: The impact of Bt corn events targeting kernel or root pests, irrigation, and climatic variables on aflatoxin- and drought-related insurance claims.

Variables	Aflatoxin-related insurance claims (2003-2016)	Drought insurance claims (2003-2016)
	Agronomic variables	
Bt corn adoption rate (only lepidopteran traits)	-0.008*** (-5.34)	-0.008*** (-10.44)

Table 3.2 (cont'd)

Variables	Aflatoxin-related insurance claims (2003-2016)	Drought insurance claims (2003-2016)
	Agronomic variables	
Bt corn adoption rate (only corn rootworm traits)	-0.006	-0.050***
	(-0.55)	(-5.72)
Bt corn adoption rate (contains both lepidopteran and corn rootworm traits)	-0.011***	-0.017***
	(-9.46)	(-23.98)
Irrigated ratio	-1.795***	-2.500***
	(-16.85)	(-36.76)
	Palmer's Z indices	
June	-0.075***	-0.151***
	(-5.06)	(-18.39)
July	-0.016	-0.297***
	(-1.13)	(-33.26)
August	0.041***	-0.155***
	(3.51)	(-19.99)
September	0.041***	-0.021***
	(3.64)	(-2.85)
	Proportion of days with maximum temperature above 32°C	
May	-0.013	-0.115
	(-0.07)	(-0.82)
June	2.320***	-0.247**
	(15.50)	(-2.41)
July	1.667***	1.649***
	(11.02)	(17.90)
August	1.092***	0.621***
	(7.52)	(6.95)
Constant	-13.639***	-8.650***
	(-137.99)	(-159.86)
No. of observations	12,223	12,223
Log-likelihood	-2,878.9	-7,618.0
Chi-square	3,588.7	9,982.0
Prob > chi2	0.00	0.00

*Notes: z-statistics in parentheses. *** p<0.01, ** p<0.05, * p<0.1*

These results indicate key agronomic factors that either promote or reduce aflatoxin-related or drought-related losses among corn growers. Perhaps the most novel finding is that Bt corn hybrids with traits which target corn rootworm have demonstrably reduced drought-related production risks in US commercial corn fields, through analysis of crop insurance claims. A likely mechanism is that, with the protected root system, corn plants are better able to use the water available in the soil, even in unusually dry seasons. Interestingly, the effect seems to be reduced when rootworm traits are stacked with lepidopteran traits. The hypothesis that the effects of Bt corn hybrids with corn rootworm traits and stacked hybrids on drought-related insurance claims are the same was rejected with likelihood ratio test value 23.83 and $p<0.001$. This reduction may be a function of time: stacked traits became more common in the United States after 2008; and after this year, corn rootworm populations had already begun to evolve resistance to the crystal proteins intended to target them in Bt corn. Very few US corn growers currently plant Bt corn that only contains rootworm traits; most plant stacked hybrids (USDA NASS 2020).

Additionally, similar to previous findings (Yu et al. 2020), transgenes that target corn borer are found to be associated with lower aflatoxin-related insurance claims from 2003-2016. This is likely because reduced kernel damage by corn borers results in reduced risk of *Aspergillus* infection and so of subsequent aflatoxin production. Bt corn events targeting corn rootworm did not have an independent effect on aflatoxin risk, but stacked hybrids (with protection against both lepidopteran pests and corn rootworm) appeared to have a slightly improved effect on reducing aflatoxin risk. This may be because root damage would compromise corn plants’ ability to take up water from the soil, and reduced water availability has been associated with greater aflatoxin risk (Yu et al. 2020). However, there are some potential endogeneity issues among those Bt corn adoption rates, and further research is needed.

Similar to findings in Yu et al. (2020), a dry June and a wet September, as measured by the Palmer Z indices for these months, are associated with greater aflatoxin risk. Not surprisingly, dry months through the majority of the corn planting season are associated with increased drought risk. Higher temperatures in June, July, and August are also associated with greater aflatoxin risk; but interestingly, only higher temperatures in July and August are associated with greater drought risk; a relatively warmer June is associated with lower drought risk.

Independently of climatic factors and other grower practices, insect resistance transgenes are shown to reduce both aflatoxin and drought risks in commercial US corn fields. This benefit may be eroded by the evolution of reduced sensitivity to insecticidal proteins among target insect populations. Insect populations in some regions have developed resistance to certain lepidopteran and CRW events (Gassmann 2021; Jakka et al. 2016; Reisig and Kurtz 2018; Tabashnik and Carriere 2017). This risk emphasizes the importance of managing insect resistance, to ensure that not only productivity is maintained, but also that other agronomic risks are prevented.

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CHAPTER 4

Discussion

The findings of the first research generate important information about the relationships between, (a) Vip-containing Bt corn and aflatoxin risk and (b) irrigation and aflatoxin and drought risks in southern US corn fields. The use of Vip-containing Bt corn and irrigation can reduce the aflatoxin-related insurance claims, further, and may become the important tools to improve profit among corn growers. This study also provides information about the drought/rainfall effects among corn planting seasons on aflatoxin contamination. Drought in the mid-summer and rainfall in the late summer were shown to reduce the aflatoxin-related damage, indicating that drought conditions in the corn silking stage and wetter in post-silking increase aflatoxin problems. Overall, in the face of future climate change and the declining water table, the use of transgenic Bt corn may be more useful than irrigation for corn growers.

The findings of the second research demonstrate different Bt hybrids efficacy on reducing aflatoxin- and drought-related damage. From the first study, we found that irrigation (the water available in the soil) and drought would affect the aflatoxin contamination. Thus, we assumed transgenes that target corn rootworm can reduce the aflatoxin risk because of preventing root damage to maintain the ability of water uptake in corn. However, the results only indicate that Bt corn targeting against lepidopteran pests, or both corn rootworm and lepidopteran pests is associated with lower aflatoxin risks. In contrast, more Bt events targeting corn rootworm are adopted in a county, drought-related insurance claims in corn were shown to decrease, and this is what we expected that improved efficacy of water taken in the root can reduce the drought risk. However, the issue of endogeneity in the different Bt hybrids adoption rate will need to be studied further.

Figure 4.1 shows that there is not much Bt corn that only protects against western corn rootworm being planted in the US. Most of the Bt corn hybrids that are planted in the US are either targeting to control lepidopteran pests or control both corn rootworm and lepidopteran pests. This may be a reason for the reduced effects of reducing drought risks when planting the stacked hybrids.

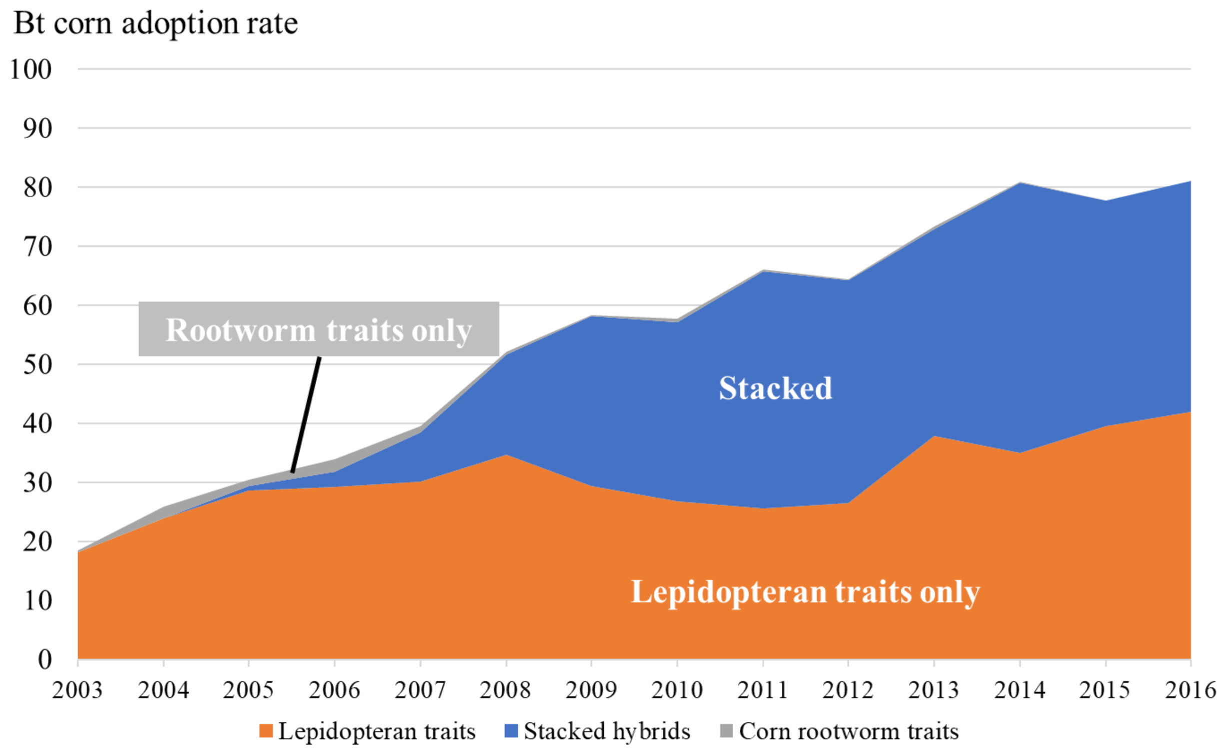

Figure 4.1 Different Bt hybrids adoption rate from 2003-2016.

In addition, we have to consider the insect resistance to Bt corn. Recently some of the studies have shown the evolution of resistance by certain lepidopteran and corn rootworm, which may reduce the Bt corn efficacy of protecting against pest damage. Moreover, the development of insect resistance may also lower Bt corn effectiveness in reducing aflatoxin and drought risks in US corn fields. In order to maintain Bt corn efficacy, the management and strategy to avoid insect resistance will be an important concern.

In conclusion, Vip-containing Bt corn and other Bt corn can be used as effective tools to improve the corn growers' profit by reducing their losses from aflatoxin or drought. Irrigation can also be another tool to reduce aflatoxin- and drought-related damage in corn fields. But when considering the future water availability and the climate change, the use of transgenic corn is likely to be more useful.