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Bt corn and cotton planting may benefit peanut growers by reducing aflatoxin risk

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Summary

Decades of studies have shown that Bt corn, by reducing insect damage, has lower levels of mycotoxins (fungal toxins), such as aflatoxin and fumonisin, than conventional corn. We used crop insurance data to infer that this benefit from Bt crops extends to reducing aflatoxin risk in peanuts: a non-Bt crop. In consequence, we suggest that any benefit–cost assessment of how transgenic Bt crops affect food safety should not be limited to assessing those crops alone; because the insect pest control offered by Bt crops affects the food safety profile of other crops grown nearby. Specifically, we found that higher Bt corn and Bt cotton planting rates in peanut-growing areas of the United States were associated with lower aflatoxin risk in peanuts as measured by aflatoxin-related insurance claims filed by peanut growers. Drought-related insurance claims were also lower: possibly due to Bt crops' suppression of insects that would otherwise feed on roots, rendering peanut plants more vulnerable to drought. These findings have implications for countries worldwide where policies allow Bt cotton but not Bt food crops to be grown: simply planting a Bt crop may reduce aflatoxin and drought stress in nearby food crops, resulting in a safer food supply through an inter-crop "halo effect."

Introduction

Bt crops are transgenic, or genetically modified, crops with transgenes from the soil bacterium *Bacillus thuringiensis* that encode for insecticidal proteins. Multiple studies have shown that Bt crop planting reduces topical insecticide use (Brookes and Barfoot, 2013; Wu, 2004), improves yields (Kathage and Qaim, 2012; Xu *et al*., 2013), and thereby increases farm incomes (Barug *et al*., 2006; Brookes and Barfoot, 2013). However, the effect is not limited to Bt-planted areas. In a so-called 'halo effect,' Bt corn planting has been shown to improve both Bt and non-Bt corn growers' yields as a result of area-wide insect pest suppression (Hutchison *et al*., 2010). Vegetable growers (non-Bt) have also benefited from pest suppression when Bt crops were grown nearby, resulting in improved yields and reduced insecticide usage on their crops (Dively *et al*., 2018).

The current study examines whether a similar halo effect exists for aflatoxin risk reduction when crops are grown in proximity to Bt crops. If this halo effect occurs, then there would be not just market benefits but potentially also health benefits to humans and animals. Aflatoxins are toxic and carcinogenic metabolites of the fungi *Aspergillus flavus* and *A. parasiticus*, which commonly infect corn, peanuts, and tree nuts when insect damage is present. Aflatoxin is the most potent naturally occurring human liver carcinogen known; "naturally occurring mixes of aflatoxins" are classified by the International Agency for Research on Cancer as a Group 1 carcinogen (Castegnaro and McGregor, 1998). Aflatoxin exposure from corn and peanut consumption is estimated to cause 25 200–155 000 cases of liver cancer globally every year (Liu and Wu, 2010). Aflatoxin exposure is also associated with stunted growth in children, immune system suppression, as well as acute toxicity and malnutrition in humans (McMillan *et al*., 2018; Saha Turna *et al*., 2023; Saha Turna and Wu, 2022; Strosnider *et al*., 2006). Bt corn has been shown to reduce aflatoxin risk (Wiatrak *et al*., 2005; Wu, 2014; Yu *et al*., 2020) by reducing insect damage, as fungi colonize crops through kernel wounds from insect feeding (Klich, 2007).

Given area-wide suppression of insect pests due to Bt crops, we hypothesized that Bt crops reduce aflatoxin damage in nearby non-Bt crops for geographic regions where aflatoxin contamination of those crops is common. Peanut is such a crop. Peanuts host insects such as *Helicoverpa zea* (corn earworm), *Spodoptera frugiperda* (fall armyworm), and *Elasmopalpus lignosellus* (lesser cornstalk borer), which also infest corn and cotton but are controlled by the Bt varieties of these crops. Of particular concern is the damage caused by the lesser cornstalk borer as it is associated with aflatoxin contamination in peanut pods (Lynch and Wilson, 1991). In the southern United States, there is geographical overlap among corn, cotton, and peanut planting regions. Due to crop rotation compatibilities (Olson and Ruberson, 2012), counties where the peanut crop is planted overlap strongly with counties where the cotton crop is planted. Corn is widely grown in the United States, including in southern peanut-growing counties (Figure 1).

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This study examined whether an inter-crop 'halo effect' from area-wide Bt corn- and cotton-induced insect suppression led to lower aflatoxin risk in peanut fields. We examined whether peanut-planting counties had fewer aflatoxin-related insurance claims filed by peanut growers when more Bt corn and cotton had been planted in that county in the years 2001–2016. The aflatoxin-related insurance claims in peanuts reflect economic loss because the peanuts are discounted or rejected whenever aflatoxin levels exceed the US Food and Drug Administration (FDA) action level: twenty micrograms per kilogramme of aflatoxin, or 20 parts per billion (ppb), in human food.

If Bt crops can protect against aflatoxin not just in those crops, but also in neighbouring crops, then there are important implications not just in the United States but worldwide. Certain countries in Africa and Asia, for example, will permit the planting of Bt cotton but not of Bt food and feed crops. Nonetheless, Bt cotton may protect against insect damage with a 'halo' effect of not just less insect damage in nearby food and feed crops but also less aflatoxin caused by insect damage. This could have important human and animal health implications, particularly in parts of the world where people consume high levels of maize and peanuts and where aflatoxin contamination of these crops is common.

Methods

Our aim was to determine whether aflatoxin risk in peanuts was lower in areas of the United States where Bt corn and/or Bt cotton were grown because of an insect controlling 'halo effect' that, we argue, would extend to peanut plants. In order to do so, we developed an aflatoxin risk model in which aflatoxin risk in peanuts is a function of the Bt crop adoption rates, temperature, drought indices, and irrigation level.

We measured aflatoxin risk as the percentage in a given year of insured peanut acreage in a county that was indemnified with the cause of loss ascribed to aflatoxin. The Risk Management Agency (RMA, an agency of the US Department of Agriculture) compiles data on county-level multi-peril crop insurance purchases and indemnities by cause of loss. The indemnities data were collected for the main growing season from June to November.

Although uninsured farms were excluded from the estimation, several facts led us to believe that any bias from selection would be negligible. One is that a large proportion of the planted area was insured; 85% of US peanut fields were insured on average from 2001 to 2016. Another is that aflatoxin is not a major cause of loss in peanut farms (Figure 2). In other words, farmers are likely

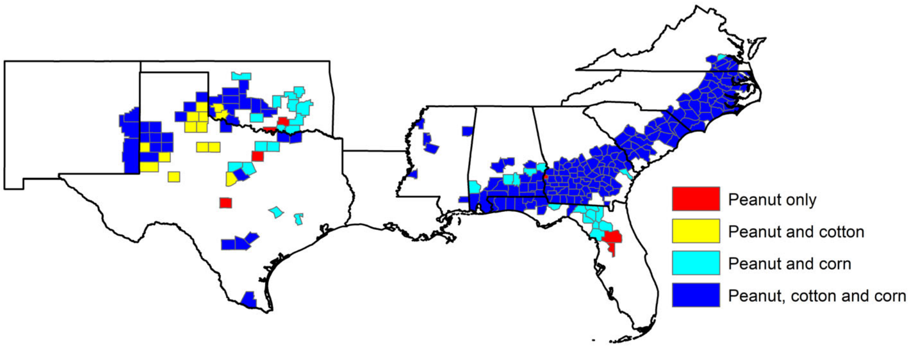

Figure 1 Overlapped peanut, cotton, and corn planting counties. Each crop's reported planting areas were averaged by year in this map, 2001–2016. Red colour: counties reporting peanut planting, but no cotton or corn. Yellow colour: counties reporting both peanut and cotton plantings. Sky blue colour: counties reporting peanut and corn plantings. Blue colour: counties reporting all three crops planting.

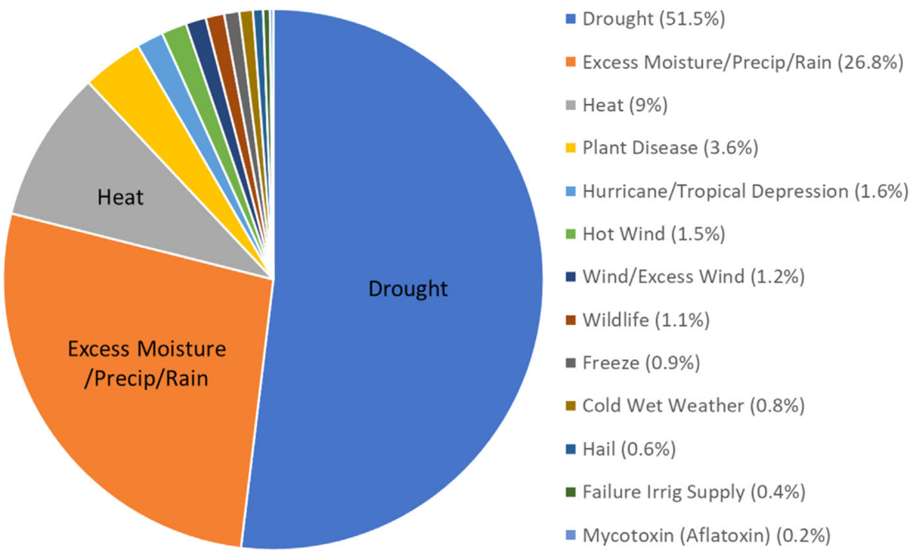

Figure 2 Shares of peanut acres by cause of loss from 2001 to 2016. The average share is represented by each segment of the pie chart.

motivated to purchase insurance in order to cover risks other than for aflatoxins. Therefore, an insured area was unlikely to have a higher probability of aflatoxin incidence than a non-insured area.

Bt crop adoption rates were measured by the percentage of Bt corn- and cotton-planted areas (numerator) in all field crops-planted areas (denominator) in a county. Bt corn adoption data by crop-reporting district level were obtained from Kynetec Ltd., a private market survey company that specializes in agricultural markets. Bt cotton adoption rate data by state, but not county, is available for 10 states, including AL, AR, CA, GA, LA, MS, MO, NC, TN, and TX. These data were obtained from the USDA National Agricultural Statistics Service (USDA NASS). We assumed that the Bt cotton/corn adoption rate was uniformly distributed within each state/crop reporting district. We believe that bias from this assumption is negligible because a minority of counties in each state have planted cotton, and these counties are largely adjacent (Figure 1). Under this assumption, the Bt corn- and Bt cotton-planted areas in each county were calculated by multiplying the Bt corn (cotton) adoption rate at the crop reporting district (or state) level by the corresponding planted areas of corn (cotton) in each county. The county-level adoption rates for Bt corn and cotton were then determined by dividing the Bt corn- and Bt cotton-planted acreage by all field crops planted acreage in each county.

Weather conditions can affect both the growth of peanuts and of *A. parasiticus* (the primary fungus that produces aflatoxin in peanuts). Environmental conditions that affect peanuts' vulnerability to fungal infection and subsequent aflatoxin contamination are drought and high temperatures (Dorner, 2008). According to experiments that controlled for daytime temperatures at 28 °C, 34 °C, 42 °C, and 48 °C, accumulated temperature >34 °C has a negative association with pollen production in peanuts (Prasad *et al*., 1999). When pod temperature is close to 35 °C (Sanders *et al*., 1984) and moisture in the pod is reduced, the pod is susceptible to fungal infection (Diener and Davis, 1977; Dorner, 2008). We generated monthly variables regarding temperature: the proportion of days on which the maximum temperature reached a certain level (36–40 °C). In July, on average 15.7% of days were exposed to this temperature range in peanuts planting counties (Table S1). Among several air temperature ranges; 32–36 °C, 34–38 °C, 36–40 °C, and 36–42 °C, the range that best fit the data to predispose peanuts to aflatoxin contamination was selected: 36–40 °C.

Water stress increases the incidence of aflatoxin by making peanut plants more susceptible to burrowing insects and fungal infections. To measure the effect of drought, we used a monthly Palmer Z-index, which is desirable for measuring agricultural drought because of its responsiveness to short-term moisture shortages (Karl, 1986).

We used the type 1 Tobit model (Wooldridge, 2010) to estimate parameters consistently by accounting for data bunching: 98% of data was piled up at zero value. Aflatoxin-related insurance claims are observed only when the risk (leading a grower to make an insurance claim) exceeds zero, so allowing for a positive probability of zero claims in a county is essential. The specific regression is described as follows:

$$y^*_{i,t} \equiv \beta_B B_{i,t} + \sum\nolimits_{m \in \{6,7,8,910\}} \left(\beta^m_Z Z^m_{i,t} + \beta^m_F M^m_{i,t}\right) + \beta_R R_i + \beta_P P_i + \beta_L L_i + \beta_T T_t + c_i + u_{i,t}; \quad (1)$$

$$y_{i,t} = \max\left(0, y^*_{i,t}\right);$$

where $y^*_{i,t}$ represents aflatoxin risk and $y_{i,t}$ measures observed aflatoxin-related insurance claims in peanuts (%) in county i and year t. The variable $B_{i,t}$ represents the Bt corn and cotton adoption rate (%) in county i and year t. Variable $Z^m_{i,t}$ is the Z-index for month m in the climate district in which the county is located, where month m is one among June, July, August, September, and October. The proportion of days with maximum temperature range between 36 and 40 °C is represented by $M^m_{i,t}$ and the year-averaged county-level proportion of irrigated land within a county is represented by R_i. A dummy variable, P_i, was included to account for potential topographical effects (Businger *et al*., 1991). This variable takes value one whenever the county is located in Alabama, Georgia, South Carolina, North Carolina, or Virginia, and takes value zero otherwise. A dummy variable, L_i, was included to represent missing data and so control for any reporting bias issues. This variable's explanatory power allowed us to test whether the occurrence of missing data correlates with aflatoxin incidence. It has value zero whenever a county has all sixteen years of covariates and value one otherwise. A vector of yearly weather conditions, T'_t, was also included where the intent is to capture weather differences between years in all peanut cultivation areas included in the analysis. This vector was measured by three variables: the growing season's year average of daily maximum temperatures, daily minimum temperatures, and daily precipitation levels. Temperature and Z-index data were obtained from the National Oceanic and Atmospheric Administration (NOAA). Irrigation data came from the United States Geological Survey (USGS).

All insured peanut-planted farms from 2001 to 2016 were included in the data set as long as the data exist. The counties were located in twelve states: Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, New Mexico, North Carolina, Oklahoma, South Carolina, Texas, and Virginia. To assess the Bt effect regardless of crop, states where Bt cotton adoption data are not available—Florida, New Mexico, Oklahoma, South Carolina, and Virginia—were included in the main analysis. However, these states were excluded from the analysis when testing the effects of Bt cotton only. The time window was chosen because indemnified peanut acres data and Bt corn adoption rate data were available for these years (Figure 3).

Unobserved county-specific characteristics c_i, such as soil quality, can also affect the aflatoxin incidence in peanuts (Winter and Pereg, 2019). To consider unobserved county-specific characteristics, we assumed that these characteristics are a function of time-averaged covariate values, $\bar{x}_i$ (i.e., the Correlated Random Effects model) (Chamberlain, 1980; Mundlak, 1978). The effects are written as $c_i = \alpha + \bar{x}_i\rho + e_i$ where α is a constant and e_i is the error term. The composite error $v_{i,t} = u_{i,t} + e_i$ is normally distributed where $u_{i,t}$ is the equation (1) error term.

The economic loss was estimated by multiplying the indemnity by a markup. Because the reported indemnity amounts are only a part of actual loss, we used the markup range 1.6–2.4 to convert indemnity to loss (Yu *et al*., 2020). Details on the markup calculation are described in the Supplementary Materials. However, minor losses associated with aflatoxin are not reported for insurance claims whenever they do not surpass loss deductibles. Losses due to aflatoxin may have actually occurred even when the reported losses were zero, as was the case in 2003, 2009, 2012, and 2013. Benefits from Bt crops were defined as the difference between estimated losses (not reported) that could include minor losses and the hypothetical losses due to aflatoxin without adopting Bt crops.

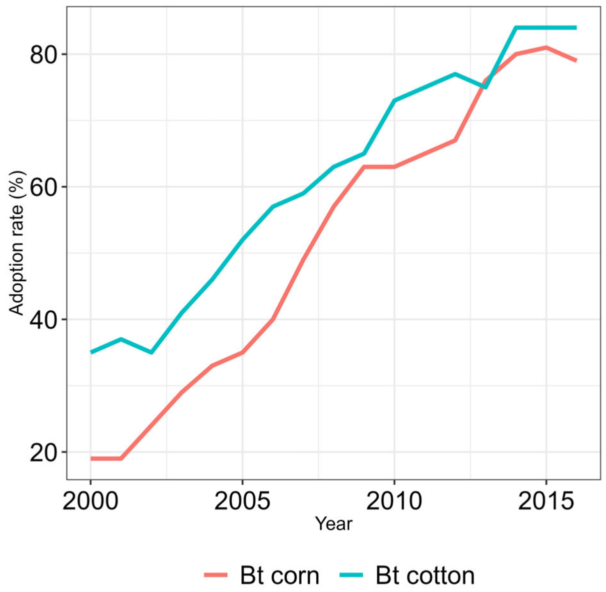

Figure 3 Bt corn and Bt cotton adoption rate among corn and cotton growers in the United States by year, 2001–2016. *Source*: USDA, Economic Research Service; https://www.ers.usda.gov/data-products/adoption-of-genetically-engineered-crops-in-the-us.aspx

Results

Impact of Bt corn and Bt cotton

Higher adoption of Bt corn and Bt cotton, although typically in the context of reducing insect damage and not primarily intended to affect either non-Bt crops or aflatoxin incidence, was associated with lower aflatoxin risk – in the form of fewer aflatoxin-caused insurance claims in peanut fields (Table 1, column 1). The −0.0008 effect indicates that a one-percentage point increase of Bt crop adoption will reduce county-level aflatoxin-related insurance claims in peanut farms by about 0.0008 percentage points. The average aflatoxin-related insurance claims among the 2248 observations were 0.0242% thus, a drop of 0.0008% indicates a 3.3% reduction rate. In other words, there was a spillover effect, or 'halo effect,' of Bt crops on reducing aflatoxin levels in peanuts.

Table 2 Economic loss caused by aflatoxin in peanuts and the economic benefits of Bt crops due to reducing aflatoxin-related damage

	Value of Peanut production	Loss due to the Aflatoxin	Benefit of Bt adoption using aflatoxin indemnities per acres	
Year	($1000)	($1000)	($1000)	Benefit of Bt over Value of production (%)
2001	1 000 512	942–1413	26.8–40.2	0.003–0.004
2002	599 714	203.7–305.5	13.8–20.8	0.002–0.003
2003	799 428	0–0	13.9–20.8	0.002–0.003
2004	813 551	35.3–52.9	1.5–2.3	0–0
2005	843 435	42.1–63.2	171.2–256.8	0.020–0.030
2006	612 798	135.4–203	294.6–441.8	0.048–0.072
2007	758 626	63.4–95.1	137.2–205.9	0.018–0.027
2008	1 193 617	11–16.5	105.8–158.6	0.009–0.013
2009	793 147	0–0	29.6–44.4	0.004–0.006
2010	938 611	1719.2–2578.8	1166.6–1749.9	0.124–0.186
2011	1 168 587	42.2–63.3	618.4–927.6	0.053–0.079
2012	2 026 326	0–0	80.5–120.8	0.004–0.006
2013	1 055 095	0–0	2.7–4	0–0
2014	1 158 251	42.9–64.4	87.4–131.1	0.008–0.011
2015	1 160 560	44.3–66.5	233.4–350	0.020–0.030
2016	1 088 165	39–58.6	368.9–553.3	0.034–0.051
Average per year	1 000 651	207.5–311.3	209.5–314.3	0.021–0.031

The loss due to aflatoxin is based on reported indemnity and does not include minor losses. The benefits were calculated based on the estimated loss, which may include minor losses.

We conducted a falsification analysis to validate the correlation between aflatoxin-related insurance claims in peanuts and Bt corn and/or cotton adoption rates. We did so by examining the relationship between Bt crop adoption rates and insurance claims for loss sources that are less likely to be affected by seed choice. The purpose of this analysis was to verify whether Bt crops are correlated with hypothetically non-related insurance

Table 1 The marginal effect of Bt crop adoption rate on peanut crop insurance claims by cause of loss

Cause of loss	Aflatoxin	Cold wet	Drought	Extra moisture	Freeze	Failure of irrigation supply
Effect	−0.0008**	−0.0003	−0.0530***	0.0084	0.0026	0.0000
	(0.0003)	(0.0009)	(0.0114)	(0.0086)	(0.0016)	(0.0004)
Observations	2248	2248	2248	2248	2248	2248
Temperature/Drought effects	Yes	Yes	Yes	Yes	Yes	Yes
County/year effects	Yes	Yes	Yes	Yes	Yes	Yes

Cause of loss	-	Heat	Hot wind	Plant disease	Wildlife	Wind
Effect	-	0.0110**	0.0075**	−0.0101***	0.0031	−0.0001
	-	(0.0050)	(0.0033)	(0.0015)	(0.0029)	(0.0015)
Observations	-	2248	2248	2248	2248	2248
Temperature/Drought effects	-	Yes	Yes	Yes	Yes	Yes
County/year effects	-	Yes	Yes	Yes	Yes	Yes

Shown are estimates of Bt corn and cotton adoption rate (%) on insurance claims by each cause of loss. Standard errors in parentheses.
$^{***}P < 0.01$, $^{**}P < 0.05$, $^{*}P < 0.1$.

Table 3 Marginal effect of Bt crop on aflatoxin-related insurance claims as estimated by a Tobit model

	Aflatoxin-related insurance claims (%)		
Variables	(1)	(2)	(3)
Bt crop adoption rate	−0.0008** (0.0003)		
Bt *corn* adoption rate		0.0006 (0.0007)	
Bt *cotton* adoption rate			−0.0009** (0.0004)
Z-index in June	0.0028 (0.0020)	0.0042 (0.0026)	0.0045** (0.0020)
Z-index in July	−0.0019 (0.0025)	−0.0005 (0.0030)	0.0017 (0.0021)
Z-index in August	−0.0011 (0.0019)	−0.0022 (0.0027)	0.0010 (0.0018)
Z-index in September	−0.0043** (0.0021)	−0.0015 (0.0022)	−0.0099*** (0.0028)
Z-index in October	0.0082*** (0.0029)	0.0102** (0.0041)	0.0045** (0.0019)
Proportion of days with temperature range between 36 and 40 °C in June	−0.0196 (0.0349)	−0.0532 (0.0473)	−0.0054 (0.0267)
Proportion of days with temperature range between 36 and 40 °C in July	0.0198 (0.0302)	−0.0171 (0.0364)	0.0370 (0.0311)
Proportion of days with temperature range between 36 and 40 °C in August	−0.0359 (0.0309)	−0.0223 (0.0382)	0.0041 (0.0251)
Proportion of days with temperature range between 36 and 40 °C in September	0.1605* (0.0881)	0.2068** (0.0923)	0.1243 (0.0847)
Proportion of days with temperature range between 36 and 40 °C in October	1.1299*** (0.3943)	1.1950** (0.5212)	0.7302*** (0.2521)
Yearly maximum temperature in June–October	0.0535*** (0.0195)	0.0521** (0.0221)	0.0555*** (0.0169)
Yearly precipitation in June–October	−0.0020 (0.0200)	−0.0136 (0.0229)	0.0224 (0.0224)
Yearly minimum temperature in June–October	−0.0138 (0.0151)	−0.0098 (0.0205)	−0.0333** (0.0138)
Piedmont dummy: 1 whenever state is AL, GA, SC, NC, VA	0.0416* (0.0236)	0.0403 (0.0273)	0.0567** (0.0241)
Missing dummy	−0.0048 (0.0079)	−0.0086 (0.0182)	0.0074 (0.0092)
Irrigation (time average, range 0–1)	−0.1141 (0.0713)	−0.1426* (0.0841)	0.0040 (0.0563)
Observations	2248	1726	1576

Bt crop adoption rate is measured by the percentage of Bt corn and cotton adopted acres to total field crop acres in each county. Standard errors in parentheses, ***$P < 0.01$, **$P < 0.05$, *$P < 0.1$.

claims in peanuts. Although such an analysis does not establish a causal relationship, the lack of associations provides evidence of robustness in our estimates of how the Bt crop affects aflatoxin-related insurance claims in peanuts.

Other USDA RMA cause-of-loss designations were collected for peanut crop insurance claims, including drought, 'extra moist,' heat, plant disease, 'hot wind,' wildlife, wind, 'cold wet,'

Table 4 Peanut plant growth stages

Growth stages	Mean day number of the year	Approximate start date in year 2023
Seedbed prepared	128	May 8
Planted	142	May 22
Emerged	163	Jun. 12
Blooming	191	Jul. 10
Pegging	199	Jul. 18
Mature	261	Sep. 18
Dug	273	Sep. 30
Harvested	291	Oct. 18

freezing temperatures, and irrigation failure. The Bt crop adoption rate was shown to be uncorrelated with peanut insurance claims caused by 'cold wet,' 'extra moist,' freeze, failure of irrigation supply, wildlife, and wind (Table 1). However, the Bt crop adoption rate was positively correlated with peanut insurance claims for heat and 'hot wind.' This may be because high temperatures lower moisture in crops, making farmers prefer Bt crops in the same region over topical insecticides that are known to be less efficient in low-moisture conditions (Leistra, 2005). Bt crops also appeared to protect peanut plants from drought damage; we found significantly fewer drought-related insurance claims where Bt crops were grown. This may be because insects that hinder the crop's water absorption by injuring roots are controlled by Bt toxins (Gianessi, 2009; Riedell, 1990). However, establishing an association between drought and Bt will require more research. The negative association between the Bt crop adoption rate and plant disease-related insurance claims in peanuts can also be explained by insect control afforded by Bt toxins. Reduced insect pest damage may reduce the risk of infection by fungi and other microbial pathogens that cause plant disease through damaged pods and stems.

The economic loss caused by discounted prices or rejection due to the aflatoxin contamination in peanuts amounted to between US $ 0.207 million and US $ 0.311 million per year, and the estimated economic loss averted due to Bt crops amounted to between US $0.209 million and US $0.314 million per year (Table 2).

We used Table 1 to assess the counterfactual of no area-wide suppression of pests due to Bt crops. We inferred that aflatoxin contamination in peanuts might then have caused roughly twice the loss that peanut growers actually incurred from 2001 to 2016. As seen in Table 2, Bt corn and cotton planting preserved about 0.03% of the total economic value of peanut production by reducing the incidence of aflatoxin contamination. This estimated benefit is purely pecuniary as captured in the market value of peanuts, and does not account for the human and animal health benefits of lower aflatoxin exposure in food and feed. Such health benefits might be even more important in countries where aflatoxin control is not strictly enforced and where Bt crops may be planted in close proximity to peanuts.

Impact of weather conditions

The effect of monthly Palmer-Z indices on aflatoxin risk in peanuts was only statistically significant in September and October (Table 3, column 1). Drought (lower Z-index value) in

Table 5 Marginal effect of Bt crops on aflatoxin-related insurance claims in peanuts as estimated by Tobit, Probit and Fractional Probit models

Variables	(1) Tobit Area-reported aflatoxin-related insurance claims (acre)	(2) Fractional Probit Aflatoxin-related insurance claims (range 0–1)	(3) Probit Aflatoxin-related insurance claims (binary)	(4) Poisson Aflatoxin-related insurance claims (%)	(5) Tobit Aflatoxin-related indemnity ($)
Bt crops adoption rate	−0.0732**	−0.0000***	−0.0005***	−0.0009***	−16.340**
	(0.0314)	(0.0000)	(0.0002)	(0.0003)	(7.114)
Z-index in June	0.4040	−0.0000	0.0025	−0.0002	82.426
	(0.2812)	(0.0000)	(0.0018)	(0.0019)	(61.769)
Z-index in July	−0.1440	−0.0001***	−0.0007	−0.0136***	−30.185
	(0.3239)	(0.0000)	(0.0021)	(0.0045)	(70.210)
Z-index in August	−0.1330	−0.0000**	−0.0009	−0.0052**	−16.896
	(0.2377)	(0.0000)	(0.0017)	(0.0021)	(51.577)
Z-index in September	−0.5543**	−0.0000	−0.0034**	−0.0028	−106.50*
	(0.2689)	(0.0000)	(0.0015)	(0.0027)	(56.069)
Z-index in October	1.0160***	0.0001***	0.0058***	0.0126***	218.29***
	(0.2796)	(0.0000)	(0.0014)	(0.0030)	(60.249)
Proportion of days with temperature range between 36 and 40 °C in June	−1.3610	−0.0006	−0.0032	−0.0744	−334.91
	(3.9106)	(0.0005)	(0.0269)	(0.0581)	(875.83)
Proportion of days with temperature range between 36 and 40 °C in July	5.5546	−0.0003	0.0229	−0.0522*	1149.5
	(4.0945)	(0.0003)	(0.0261)	(0.0311)	(914.29)
Proportion of days with temperature range between 36 and 40 °C in August	−4.2545	−0.0006**	−0.0226	−0.0661***	−908.38
	(4.1061)	(0.0002)	(0.0250)	(0.0256)	(886.64)
Proportion of days with temperature range between 36 and 40 °C in September	23.118**	0.0024***	0.0508	0.2507***	5262.0**
	(10.099)	(0.0007)	(0.0473)	(0.0662)	(2196.4)
Proportion of days with temperature range between 36 and 40 °C in October	178.98***	0.0093***	1.0751***	1.1677***	37611***
	(58.921)	(0.0033)	(0.3176)	(0.4408)	(13465)
Yearly maximum temperature in June–October	6.4803***	0.0006***	0.0370***	0.0640***	1440.3***
	(2.0530)	(0.0002)	(0.0094)	(0.0223)	(447.60)
Yearly precipitation in June–October	−0.6040	−0.0000	−0.0076	−0.0052	−193.01
	(2.5133)	(0.0002)	(0.0170)	(0.0259)	(559.15)
Yearly minimum temperature in June–October	−1.4206	−0.0002	−0.0060	−0.0205	−340.74
	(1.6761)	(0.0002)	(0.0107)	(0.0189)	(364.09)
Piedmont dummy: 1 whenever state is AL, GA, SC, NC, VA	4.1237	0.0002	0.0356**	0.0331	646.53
	(2.9730)	(0.0003)	(0.0162)	(0.0512)	(588.26)
Missing dummy	−0.3158	0.0000	−0.0070	0.0086	−24.969
	(0.9081)	(0.0001)	(0.0065)	(0.0091)	(201.75)
Irrigation (time average, range 0–1)	−28.561***	−0.0036***	−0.0647	−0.4488***	−5519.9***
	(9.7515)	(0.0011)	(0.0493)	(0.1397)	(1966.8)
Insured area	0.0003***				0.0630***
	(0.0001)	-	-	-	(0.0191)
Insurance coverage	-	-	-	-	6221.0**
					(2476.3)
Observations	2248	2248	2248	2248	2248

Standard errors in parentheses, ***$P < 0.01$, **$P < 0.05$, *$P < 0.1$.

September raised the incidence of aflatoxin. Given the fact that the 'dug date,' the date at which peanut pods are lifted from the soil before harvest, occurred on September 30 on average (Table 4), we inferred that drought before digging was positively correlated with high aflatoxin infestation by raising the water stress imposed on peanuts (Dorner, 2008). Drought in October, on the other hand, was associated with a lower aflatoxin risk. The divergent within-year temporal impacts of drought imply that drying well after the dug date reduced aflatoxin production. Temperature effects also indicated that September and October were the critical months for the incidence of aflatoxin in peanuts. High temperatures in these months were both associated with a high number of aflatoxin-related insurance claims.

Robustness checks

We included further analyses to test result robustness. First, we estimated Bt and weather impacts on the aflatoxin-related insurance-claimed area instead of on aflatoxin-related insurance claims as a percent of insured acres in a county. Second, we

Table 6 Marginal effect of alternative temperature ranges on aflatoxin-related insurance claims in peanuts estimated by Tobit models

Variables	(1) Tobit Aflatoxin-related insurance claims (%)	(2) Tobit Aflatoxin-related insurance claims (%)	(3) Tobit Aflatoxin-related insurance claims (%)
Bt crops adoption rate (Bt corn and cotton planted area /field crops planted area)	−0.0007*	−0.0006*	−0.0007**
	(0.0004)	(0.0004)	(0.0004)
Z-index in June	0.0046*	0.0023	0.0028
	(0.0026)	(0.0023)	(0.0020)
Z-index in July	−0.0036	0.0001	−0.0014
	(0.0030)	(0.0027)	(0.0025)
Z-index in August	−0.0014	−0.0030	−0.0013
	(0.0018)	(0.0024)	(0.0020)
Z-index in September	−0.0044*	−0.0027	−0.0046**
	(0.0025)	(0.0019)	(0.0022)
Z-index in October	0.0087***	0.0080***	0.0087***
	(0.0028)	(0.0026)	(0.0030)
Proportion of days with temperature in 32–36 °C range in June	0.0135		
	(0.0277)		
Proportion of days with temperature in 32–36 °C range in July	−0.0127		
	(0.0251)		
Proportion of days with temperature in 32–36 °C range in August	−0.0042		
	(0.0234)		
Proportion of days with temperature in 32–36 °C range in September	0.0529*		
	(0.0274)		
Proportion of days with temperature in 32–36 °C range in October	−0.0403		
	(0.0712)		
Proportion of days with temperature in 34–38 °C range in June		0.0132	
		(0.0293)	
Proportion of days with temperature in 34–38 °C range in July		0.0127	
		(0.0249)	
Proportion of days with temperature in 34–38 °C range in August		−0.0368	
		(0.0267)	
Proportion of days with temperature in 34–38 °C range in September		0.1407***	
		(0.0445)	
Proportion of days with temperature in 34–38 °C range in October		0.7832*	
		(0.4077)	
Proportion of days with temperature in 36–42 °C range in June			−0.0230
			(0.0350)
Proportion of days with temperature in 36–42 °C range in July			0.0163
			(0.0314)
Proportion of days with temperature in 36–42 °C range in August			−0.0414
			(0.0338)
Proportion of days with temperature in 36–42 °C range in September			0.1613*
			(0.0916)
Proportion of days with temperature in 36–42 °C range in October			0.9571**
			(0.4318)
Yearly maximum temperature in June–October	0.0498***	0.0399**	0.0554***
	(0.0183)	(0.0170)	(0.0202)
Yearly precipitation in June–October	−0.0014	−0.0007	−0.0039
	(0.0242)	(0.0214)	(0.0195)
Yearly minimum temperature in June–October	−0.0162	−0.0311*	−0.0140
	(0.0174)	(0.0162)	(0.0152)
Piedmont dummy: 1 when state is AL, GA, SC, NC, VA	0.0272	0.0598**	0.0421*
	(0.0241)	(0.0290)	(0.0235)
Missing dummy	−0.0175**	−0.0237***	−0.0055
	(0.0085)	(0.0087)	(0.0078)
Irrigation (time average, ranges 0–1)	−0.0884	−0.0200	−0.1303*
	(0.0707)	(0.0539)	(0.0702)
Observations	2248	2248	2248

Standard errors in parentheses, ***$P < 0.01$, **$P < 0.05$, *$P < 0.1$.

replaced the tobit model estimation with fractional probit, probit, and Poisson model estimations (Wooldridge, 2010). For the fractional probit and probit models, the dependent variable was converted to having range [0, 1] and binary value, respectively. Third, we estimated the effect of Bt crop adoption rate on claimed *indemnity amount* ($) for aflatoxin. The differences from the main model are that the dependent variable is the indemnity amount caused by aflatoxin whistle two additional variables were included (average insurance coverage and insured area) because indemnity values in a county depend on the level of insurance coverage, the insured area, and the incidence of aflatoxin (Yu *et al*., 2020). The estimated coefficients were used to calculate the hypothetical indemnity due to aflatoxin without Bt crops adoption. The results from these robustness checks (Table 5) were consistent with the main results, i.e., Bt corn and cotton were associated with lower aflatoxin risk in peanuts.

Separate effects for Bt corn and Bt cotton were also considered. Columns 2 and 3 in Table 3 indicate, respectively, the effects of Bt corn and Bt cotton planting on aflatoxin-related insurance claims among peanut growers, whereas the Bt corn effect was not statistically significant, the Bt cotton effect was significant. The estimated Bt cotton effect was stronger than the estimated Bt corn effect, likely because cotton shares more common planting areas with peanut fields than does corn. RMA and NASS data show that for counties having peanut crop insurance, the average cotton-planted area (33 682 acres) was much larger than the average corn area (9666 acres). The cotton-planted area accounts for 46% of the total field crops area on average, but the corn-planted area accounts for 21% of the total cropped area within peanut-growing counties. Also, the average Bt cotton adoption rate was higher (36.1%) than the Bt corn adoption rate (8.8%) within peanut planting counties. We conclude that the Bt halo effect of aflatoxin risk reduction arising from reducing insect pests depends mainly on Bt cotton rather than Bt corn.

Table 6 presents the results for alternative temperature ranges. Columns 1, 2, and 3 indicate the effect of temperature ranges of 32–36 °C, 34–38 °C, and 36–42 °C, respectively. The responses were similar to those in the main result (column 1 in Table 3).

Discussion

This study is the first to show evidence of a 'halo' effect in how Bt crop plantings benefit non-adopters by reducing aflatoxin contamination through area-wide suppression of insects that promote fungal infection. Although Bt peanut seed is not commercially available, peanut growers benefit from the presence of Bt corn and Bt cotton crops nearby through the reduction of aflatoxin in their peanuts, providing safer food and improved market returns.

Peanuts are an important crop in many developing countries worldwide. Although it has long been suggested that stricter food safety standards in high-income importing countries are a major impediment to market penetration by developing countries (Ferro *et al*., 2015; Martins *et al*., 2023; Meneely *et al*., 2023; Otsuki *et al*., 2001; Wu, 2004), domestic supply constraints are likely more detrimental to market development (Hejazi *et al*., 2022; Jin *et al*., 2024; Xiong and Beghin, 2012). Whether peanuts are intended for domestic or export markets, storage and other forms of quality protection are significant supply constraints. Incentives for investing in quality protection along the food chain diminish when peanuts are already damaged by harvest time. Therefore, any means to reduce aflatoxin damage in peanuts in the field are beneficial. Many nations worldwide plant Bt corn and cotton, in addition to peanuts (ISAAA, 2019). If these crops are grown in close proximity, the halo effect the Bt crops provide to reduce common insect pests may result in benefits of aflatoxin reduction in peanuts that would have implications not just for improving domestic and possibly export markets but also human health.

It is also important to note some limitations to our analysis. Crop rotation practices between cotton and peanuts may result in an underestimation of the impact of Bt cotton on peanut aflatoxin damage. Bt cotton is less likely to be planted in a cotton-peanut rotation because cotton farmers that use the Bt technology may see less need for controlling their primary crop through rotations, and so the true effect of Bt cotton on peanut aflatoxin damage may be underestimated. Additionally, the measured Bt crop adoption rate may be lower than the actual value due to the absence of some relevant Bt cotton data. The Bt cotton data are unavailable from USDA NASS for certain states with low cotton production, such as FL, NM, OK, SC, and VA. This likely further contributes to an underestimation of the impact of Bt cotton on aflatoxin contamination in peanuts.

Author contributions

Jina Yu: Conceptualization, methodology, formal analysis, investigation, writing – original draft. **David A. Hennessy**: Conceptualization, methodology, resources, writing – review and editing, funding acquisition. **Felicia Wu**: Conceptualization, methodology, resources, writing – review and editing, funding acquisition.

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Conflict of interest

The authors declare no competing interests.

Data availability

Insurance indemnity data are available at http://www.rma.usda.gov/data, while weather data are available at http://www1.ncdc.noaa.gov. Bt corn adoption rate data were purchased from Kynetec. Bt cotton adoption rate data are from the USDA, Economic Research Service; https://www.ers.usda.gov/data-products/adoption-of-genetically-engineered-crops-in-the-us.aspx.

References

Barug, D., Bhatnagar, D., van Egmond, H.P., van der Kamp, J.W., van Osenbruggen, W.A. and Visconti, A. (Eds.). (2006) *The mycotoxin factbook*. https://doi.org/10.3920/978-90-8686-587-1

Brookes, G. and Barfoot, P. (2013) *GM crops: Global socio-economic and environmental impacts 1996–2011*, p. 187. Dorchester, UK: PG Economics Ltd.

Businger, S., Bauman, W.H., III and Watson, G.F. (1991) The development of the Piedmont front and associated outbreak of severe weather on 13 March 1986. *Mon. Weather Rev.* **119**, 2224–2251.

Castegnaro, M. and McGregor, D. (1998) Carcinogenic risk assessment of mycotoxins. *Rev. Med. Vet.* **149**, 671–678.

Chamberlain, G. (1980) Analysis of covariance with qualitative data. *Rev. Econ. Stud.* **47**, 225–238.

Diener, U.L. and Davis, N.D. (1977) *Aflatoxin Formation in Peanuts by Aspergillus Flavus*, p. 493. Alabama Agricultural Experiment Station: Auburn University.

Dively, G.P., Venugopal, P.D., Bean, D., Whalen, J., Holmstrom, K., Kuhar, T.P., Doughty, H.B. *et al*. (2018) Regional pest suppression associated with widespread Bt maize adoption benefits vegetable growers. *Proc. Natl. Acad. Sci.* **115**, 3320–3325.

Dorner, J. (2008) Management and prevention of mycotoxins in peanuts. *Food Addit. Contam.* **25**, 203–208.

Ferro, E., Otsuki, T. and Wilson, J.S. (2015) The effect of product standards on agricultural exports. *Food Policy* **50**, 68–79.

Gianessi, L. (2009) *The Benefits of Insecticide Use: Peanuts*, p. 10. Washington, DC: Croplife Foundation.

Hejazi, M., Grant, J.H. and Peterson, E. (2022) Trade impact of maximum residue limits in fresh fruits and vegetables. *Food Policy* **106**, 102203.

Hutchison, W., Burkness, E.C., Mitchell, P.D., Moon, R.D., Leslie, T.W., Fleischer, S.J., Abrahamson, M. *et al*. (2010) Areawide suppression of European corn borer with Bt maize reaps savings to non-Bt maize growers. *Science* **330**, 222–225.

ISAAA. (2019) *SAAA Brief 55–2019: Executive summary: Biotech crops drive socio-economic development and sustainable environment in the new frontier*. https://www.isaaa.org/resources/publications/briefs/55/executivesummary/default.asp [Last accessed June 2024]

Jin, S., Ma, B., Zheng, Y., Jin, X. and Wu, W. (2024) Short-term impact of food safety standards on agri-product exports: Evidence from Japan's positive list system on Chinese vegetable exports. *J. Agric. Econ.* **75**, 362–381.

Karl, T.R. (1986) The sensitivity of the Palmer drought severity index and Palmer's Z-index to their calibration coefficients including potential evapotranspiration. *J. Clim. Appl. Meteorol.* **25**, 77–86.

Kathage, J. and Qaim, M. (2012) Economic impacts and impact dynamics of Bt (*Bacillus thuringiensis*) cotton in India. *Proc. Natl. Acad. Sci.* **109**, 11652–11656.

Klich, M.A. (2007) Aspergillus flavus: The major producer of aflatoxin. *Mol. Plant Pathol.* **8**, 713–722.

Leistra, M., 2005. *Estimating input data for computations on the volatilisation of pesticides from plant canopies and competing processes. Wageningen Alterra 1256*.

Liu, Y. and Wu, F. (2010) Global burden of aflatoxin-induced hepatocellular carcinoma: A risk assessment. *Environ. Health Perspect.* **118**, 818.

Lynch, R. and Wilson, D. (1991) Enhanced infection of peanut, *Arachis hypogaea* L., seeds with aspergillus flavus group fungi due to external scarification of peanut pods by the lesser cornstalk borer, elasmopalpus lignosellus (Zeller). *Peanut Science* **18**, 110–116.

Martins, L.M., Bragagnolo, N., Calori, M.A., Iamanaka, B.T., Alves, M.C., da Silva, J.J., de Godoy, I.J. *et al*. (2023) Assessment of early harvest in the prevention of aflatoxins in peanuts during drought stress conditions. *Int. J. Food Microbiol.* **405**, 110336.

McMillan, A., Renaud, J.B., Burgess, K.M.N., Orimadegun, A.E., Akinyinka, O.O., Allen, S.J., Miller, J.D. *et al*. (2018) Aflatoxin exposure in Nigerian children with severe acute malnutrition. *Food Chem. Toxicol.* **111**, 356–362.

Meneely, J.P., Kolawole, O., Haughey, S.A., Miller, S.J., Krska, R. and Elliott, C.T. (2023) The challenge of global aflatoxins legislation with a focus on peanuts and peanut products: a systematic review. *Exposure and Health* **15**, 467–487.

Mundlak, Y. (1978) On the pooling of time series and cross section data. *Econometrica* **46**, 69–85.

Olson, D. and Ruberson, J. (2012) Crop-specific mortality of southern green stink bug eggs in Bt-and non-Bt cotton, soybean and peanut. *Biocontrol. Sci. Techn.* **22**, 1417–1428.

Otsuki, T., Wilson, J.S. and Sewadeh, M. (2001) Saving two in a billion: Quantifying the trade effect of European food safety standards on African exports. *Food Policy* **26**, 495–514.

Prasad, P.V., Craufurd, P. and Summerfield, R. (1999) Fruit number in relation to pollen production and viability in groundnut exposed to short episodes of heat stress. *Ann. Bot.* **84**, 381–386.

Riedell, W.E. (1990) Rootworm and mechanical damage effects on root morphology and water relations in maize. *Crop. Sci.* **30**, 628–631.

Saha Turna, N. and Wu, F. (2022) Estimation of tolerable daily intake (TDI) for non-carcinogenic effects of aflatoxin. *Risk Anal.* **42**, 431–438.

Saha Turna, N., Comstock, S.S., Gangur, V., Chen, C. and Wu, F. (2023) Effects of aflatoxin on the immune system: Evidence from human and animal research. *Crit. Rev. Food Sci. Nutr.* **7**, 1–19.

Sanders, T.H., Blankenship, P.D., Cole, R.J. and Hill, R.A. (1984) Effect of soil temperature and drought on peanut pod and stem temperatures relative to Aspergillus flavus invasion and aflatoxin contamination. *Mycopathologia* **86**, 51–54.

Strosnider, H., Azziz-Baumgartner, E., Banziger, M., Bhat, R.V., Breiman, R., Brune, M.N., DeCock, K. *et al*. (2006) Workgroup report: public health strategies for reducing aflatoxin exposure in developing countries. *Environ. Health Perspect.* **114**, 1898–1903.

Wiatrak, P., Wright, D., Marois, J. and Wilson, D. (2005) Influence of planting date on aflatoxin accumulation in Bt, non-Bt, and tropical non-Bt hybrids. *Agron. J.* **97**, 440–445.

Winter, G. and Pereg, L. (2019) A review on the relation between soil and mycotoxins: Effect of aflatoxin on field, food and finance. *Eur. J. Soil Sci.* **70**, 882–897.

Wooldridge, J.M. (2010) *Econometric analysis of cross section and panel data*, 2nd edn. Cambridge, MA: MIT Press.

Wu, F. (2004) Explaining public resistance to genetically modified corn: An analysis of the distribution of benefits and risks. *Risk Anal.* **24**, 715–726. https://doi.org/10.1111/j.0272-4332.2004.00470.x

Wu, F. (2014) Perspective: Time to face the fungal threat. *Nature* **516**, S7.

Xiong, B. and Beghin, J. (2012) Does European aflatoxin regulation hurt groundnut exporters from Africa? *Eur. Rev. Agric. Econ.* **39**, 589–609.

Xu, Z., Hennessy, D.A., Sardana, K. and Moschini, G. (2013) The realized yield effect of genetically engineered crops: US maize and soybean. *Crop. Sci.* **53**, 735–745.

Yu, J., Hennessy, D.A. and Wu, F. (2020) The impact of Bt corn on aflatoxin-related insurance claims in the United States. *Sci. Rep.* **10**, 1–10.

Supporting information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Supplementary Materials Economic benefit of Bt crops.
Table S1 Percentage of days in each temperature range, on average.