LETTER

Climate change will increase aflatoxin presence in US Corn

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Abstract

The impacts of climate change on agricultural production are a global concern and have already begun to occur (Kawasaki 2018 Am. J. Agric. Econ. 101 172–92; Ortiz-Bobea et al 2021 Nat. Clim. Change 11 306–12), with major drivers including warmer temperatures and the occurrence of extreme weather events (Lobell and Field 2007 Environ. Res. Lett. 2 014002; Challinor et al 2014 Nat. Clim. Change 4 287; Rosenzweig et al 2001 Glob. Change Hum. Health 2 90–104; Schlenker and Roberts 2009 Proc. Natl Acad. Sci. USA 106 15594–8; Lobell et al 2014 Science 344 516–9; Ortiz-Bobea et al 2019 Environ. Res. Lett. 14 064003). An important dimension of the climate change-crop yield relationship that has often been overlooked in the empirical literature is the influence that warming temperatures can have on plant damage arriving through biotic channels, such as pest infestation or fungal infection (Rosenzweig et al 2001 Glob. Change Hum. Health 2 90–104). Aflatoxins are carcinogenic chemicals produced by the fungi Aspergillus flavus and A. parasiticus, which commonly infect food crops. Currently, in the United States, aflatoxin is a perennial contaminant in corn grown in the South, but rare in the Corn Belt and northern states. Climate change may expand aflatoxin’s geographical prevalence, however; because hot, dry summers promote aflatoxin accumulation. Here we model aflatoxin risk as a function of corn plant growth stages and weather to predict US regions with high aflatoxin risk in 2031–2040, based on 16 climate change models. Our results suggest that over 89.5% of corn-growing counties in 15 states, including the Corn Belt, will experience increased aflatoxin contamination in 2031–2040 compared to 2011–2020. Interestingly, the results are spatially heterogeneous and include several southern counties expected to have lower aflatoxin risk, because the causative fungi become inactivated at very high temperatures.

1. Introduction

Temperature effects have been demonstrated to have a compounding influence on both average crop yields and yield risks, have already begun to produce discernible effects, and can operate through biotic channels like pest damage [1, 2] and abiotic channels encompassing both heat- and water-related stress, according to numerous studies [3–13]. Aflatoxin contamination is one of these risks, as it is likely to increase under a changing climate because of its association with warm and dry temperatures [14, 15]. Aflatoxin is a mycotoxin, or fungal toxin, produced by the fungi Aspergillus flavus and A. parasiticus in corn, peanuts, and tree nuts grown in warm climates. As the most potent natural liver carcinogen known, aflatoxin causes between 25,000 and 155,000 cases of liver cancer annually worldwide [16]. Aside from its carcinogenic effects, chronic aflatoxin exposure is associated with child growth.
impairment [17] and malnutrition in humans [18]. In the United States, aflatoxin levels in corn intended for human consumption and animal feed are regulated by the Food and Drug Administration, thus health hazards are normally modest; the greatest loss is to corn producers from rejected lots with high aflatoxin levels. Aflatoxin contaminated crop is discounted or destroyed depending on contamination level. The Aspergillus fungi that produce aflatoxin thrive on field crops in hot, dry conditions [19]. Multiple review papers have suggested that increased temperatures and drought stress increase aflatoxin occurrence [15, 20–22]. However, less research has focused on empirically studying the relationship between predicted future climate scenarios and aflatoxin risk. Battilani et al [14] projected that the risk of A. flavus contaminations is likely to increase in corn when daily temperature increases by either 2 °C or 5 °C in southern Europe. They also forecast that Greece, southern Italy, Bulgaria, and Albania may have high aflatoxin risks due to expected increases in daily temperatures by 2 °C [14]. Conversely, in the Philippines Salvacion et al [23] projected that the risk of aflatoxin contamination is expected to decrease in the near future, due to increased rainfall.

This study projects aflatoxin risk in the United States in the years 2031–2040 under 16 climate change models. As the US is by far the world’s largest corn-producing country, understanding aflatoxin risk in the near future in US corn is meaningful for global food security. A common assumption made in studies predicting future crop production is that a crop’s future growing season will be unaffected by climate change [24–26]. However, it is more reasonable to expect that farmers will adjust planting seasons to adapt to changing climates, which will consequently change annual dates for the crop’s growth stages and vulnerability to fungal infection [27, 28]. A year-location specific growth season is critical to predict future aflatoxin risk because weather condition right after silking (AS) season is associated with fungal infection [29]. In other words, weather variable during this season that varies in year and location is important for future prediction under climate change. We account for this shift directly in our analysis by modelling future corn growing seasons as a function of projected weather conditions to provide estimates of future aflatoxin risks that are robust to growing season adaptations. Our empirical response function relating aflatoxin occurrence to weather is estimated by combining conventional statistical approaches with large-scale spatial and temporal data measuring actual on-farm yield losses tied directly to aflatoxin.

2. Historical data

We used historical data on temperature, precipitation, and irrigation to build our aflatoxin-climate model parameters. For precipitation, each county’s total precipitation and square of total precipitation were used. Drought weakens corn, making it susceptible to fungal infection; and because A. flavus commonly infects corn soon AS, drought can increase aflatoxin risk in this stage [29]. After this stage, weather conditions mainly affect aflatoxin production given the initial infection level. Thus we included precipitation variables both in the main fungal infection season (AS) and after dent emergence (hereafter referred to as AD).

Temperature variables that were included in the model were measured by the time exposure to certain temperature ranges: 22 °C–26 °C, 26 °C–36 °C, and 36 °C+ in AS and 22 °C–26 °C, 26 °C–30 °C, and 30 °C+ in AD. Time exposure to each 1 °C increment is estimated from a sinusoidal function of daily maximum and minimum temperature [24, 30]. From the multiple temperature range sets, we choose the cutoff temperatures (26 °C and 36 °C in AS; 26 °C and 30 °C in AD) that best fit the data [4]. Because our purpose is to see the detrimental effect of temperature on aflatoxin that has positively associated with high temperature, we used time exposure to temperature ranges rather than degree days, a common temperature index. Our index evaluates hourly exposure to lower and higher temperature range along with the favored ranges to aflatoxin occurrence, whereas the degree days measure daily exposure to a given temperature range.

Since temperature ranges that promote or restrict aflatoxin production vary by corn growth stage, we used different temperature ranges in AS and AD as well. To create the AS and AD seasons’ temperature/precipitation variables, we obtained crop growing stage period data from the USDA National Agricultural Statistics Service (NASS) [31]. These data provide the percentage of acres that have reached a growth stage in a given week and state. We linearly interpolate daily values from weekly values and extrapolate the values to have 0%–100% range in case the starting value of record is not 1 or the ending value of record is not 100 [32]. From time exposure to each 1 °C, we calculate total time exposure to certain temperature ranges in each season. The daily maximum and minimum temperature and precipitation data were drawn from the Parameter-elevation Regressions on Independent Slopes Model dataset [24].

Irrigation is known to mitigate aflatoxin risk by reducing drought stress [33]. This study includes the county-level proportion of irrigated land. County level irrigation data were obtained from the US Geological Survey (USGS). Because the data were only available in 2005, 2010, and 2015, we assumed that irrigated areas have not changed substantially over five-year periods to avoid large number of missing observations. Total acres in each county data are from the US Census Bureau.
Aflatoxin risk is measured by the ratio of area with insurance claimed for aflatoxin to insured area in a county. The USDA Risk Management Agency (RMA) provides county level insurance information such as premium, reported area and indemnity for aflatoxin, which we use as a proxy for nation-wide aflatoxin risk in commercial corn fields [5]. Specifically, we obtained data on acres with crop insurance claims regarding aflatoxin and then divided these by insured acres. The USDA RMA provides data on insured and indemnified acres, and the amount of indemnity for each crop and county, as well as cause of loss. These data have two notable limitations. One is that only claims recorded are on insured land units. However, because crop insurance covered 91% of corn planting areas from 2011 to 2020 for the 15 states that we consider, this will not have a significant impact on the study’s results. The other limitation is that insurance contracts carry deductibles, which generally account for 15%–50% of expected crop values. The average size of the deductible varies by crop and by location, but has generally declined over the past quarter century. Consequently, minor incidences of aflatoxin-related loss that do not trigger an insured loss are not recorded, while the incidence of losses that are not reported varies somewhat across states and over time.

To estimate the economic impact of aflatoxin, indemnity per premium is used. Indemnity amount represents severity of aflatoxin as well as aflatoxin incidence. However, indemnity varies due to corn price, insurance contract type, and coverage level. To minimize bias from aggregation, we normalized indemnity amount by using indemnity dollar paid per premium dollar paid [4]. To examine the impact of temperature and drought in the corn growing stage, and not storage-related events, we collected insurance claims data for only the months of June through September, when aflatoxin events are most likely to occur in the field.

This analysis covered 15 Southern and Midwestern states that have claimed indemnities for aflatoxin losses from crop insurance companies marketing USDA supported multiple peril contracts: Alabama, Arkansas, Illinois, Iowa, Kansas, Kentucky, Louisiana, Missouri, Mississippi, North Carolina, Nebraska, Oklahoma, Tennessee, Texas, and Virginia. Georgia and South Carolina are excluded in the analysis because reported crop progress data are unavailable.

3. Methods

The main estimation model extends the approach in Yu et al [34]. Specifically, the historical relationship between temperature, precipitation, and irrigation and aflatoxin risk is estimated by the following reduced form:

\[ y_{c,t}^* = \beta_0 + \sum_{g \in \{\text{AS, AD}\}} \left( \sum_i (\beta_{c,i}^g P_{c,i,t}^g) + \beta_{c,t}^g P_{c,t}^g + \beta_{s,t}^g P_{s,t}^g \right) + \beta_B R_{c,t} + \beta_T T + \beta_S + \alpha_{c,t} + u_{c,t}; \]

where \( y_{c,t}^* \) is aflatoxin risk as measured by aflatoxin-related insurance claims (the percentage of acres claimed for aflatoxin in county \( c \), state \( s \) and year \( t \)); \( P_{c,i,t}^g \) is time exposure to the temperature ranges \( i \) in county \( c \), state \( s \), and year \( t \) during period \( g \), where \( g \) is either the AS or the AD season and temperature range \( i \) varies in \( g \); \( P_{c,t}^g \) is precipitation in the AS or the AD season; \( P_{s,t}^g \) is the square of precipitation; \( R_{c,t} \) is proportion of irrigated area to total area within a county; \( T \) is a vector of year dummies; \( S \) is a vector of state dummy variables; \( \alpha_{c,t} \) is the county-specific unobserved factor; and \( u_{c,t} \) is a normally distributed error term. The calendar dates of the AD and AS seasons, described by superscript \( g \), vary by state and year.

We estimated the above model using Type I Tobit specifications to account for the fact that 94% of aflatoxin-related insurance claims in our historical data were zeroes; i.e. in most counties in most years, no aflatoxin-related insurance claims were made by corn growers. This model allows for a positive probability that aflatoxin-related insurance claims are zero, \( \Pr(y_{c,t}^* = 0) > 0 \) [35].

County-specific effect was estimated by correlated random effect [36, 37] in which we assume that unobserved factors are functions of the time averaged value of covariates. Details are explained in the supplementary materials (available online at stacks.iop.org/ERL/17/054017/mmedia). The estimated results are reported in supplementary table 1 (S. table 1). Standard errors clustered at the crop reporting district (CRD)-by-year level.

3.1. Robustness check

We considered alternative assumptions on the spatial correlation of the residuals, as well as alternative estimators and measures of risk. First, we reported standard errors clustered at the state-by-year level (S. table 2 column (1) and county level (column (2))). While the former allows for spatial correlation among counties within a state, the latter does not allow for spatial correlation. Second, we also consider the quasi-maximum likelihood estimate Poisson [38] specification (column (3) and (4)). Finally, we alternatively measure the economic risk of aflatoxin by indemnified dollar amount per liability (column (5)) and indemnified dollar amount per premium (column (6)). Overall results are consistent with our main results. Details are explained in the supplementary materials.
3.2. Predicting corn growth stages
This model extends the approach of Yu et al [34] by including crop-stage specific variables to capture weather exposure. This is an important distinction to make as these stages do not occur during the same calendar dates across locations and time in-sample (S. tables 3 and 4), so measuring weather based on fixed dates (e.g. weekly or monthly) would likely induce measurement error. This concern is made more pressing by the existing evidence suggesting heterogeneous effects of weather on aflatoxin risk across growth stages [29].

To predict farmers’ planting decisions in accordance with changing climate conditions, we predicted the optimal planting period with the highest expected yield from potential planting dates [27]. We considered seven scenarios for potential planting dates by allowing one, two, and three weeks variation in either direction from the current planting date [27]. We assume that yield is a function of growing degree days (GDD) and killing degree days (KDD) measuring damaging heat unit, during main growing stages; planting to silking (phase 1), silking to dough (phase 2), dough to mature stage (phase 3), and precipitation [32]:

$$Yield_{c,t} = \beta_0 + \sum_{p=1}^{3}(\beta_{GDD,p}GDD_{p,c,t} + \beta_{KDD,p}KDD_{p,c,t})$$

$$+ \beta_{Rain}Rain_{c,t} + \beta_{Year}Year + \epsilon_{c,t};$$

(2)

where Yield is measured in bu/acre per each county (c) and year (t); p indicates each growth phase. $\beta_{GDD,p}$ and $\beta_{KDD,p}$ represent each phase’s GDD and KDD effect on yields; $\beta_{Rain}$ and $\beta_{Year}$ indicate respective rain and linear year response coefficients; and $\beta_0$ estimates county specific characteristics, which are measured by the fixed effect model [35]. From 1981 through 2020, all corn planting counties in the US were included, but states without phase data were removed. Each day’s GDD and KDD calculations are as followed by Butler et al [32]. Table 1 shows the regression results. Heat values over the AS and AD time intervals were predicted by adding the accumulated GDD from the predicted planting dates [39].

3.3. Future weather variables
To project aflatoxin risk in the period 2031–2040, we used daily maximum and minimum temperatures and precipitation data from 16 climate change models. Each climate model provides values for historical temperature/precipitation and for forecasted temperature/precipitation. We calculated daily temperature and precipitation values over 2031–2040 for each model by adding the average daily difference for each model to the historical, daily, temperature and precipitation value [40]. Detail of calculation is described in the supplementary materials.

| Table 1. Effect on GDD, KDD and rain on yield. |
|----------------|----------------|
| Variables | Yield |
| GDD-phase1 | 0.022\(^{**}\) (0.001) |
| KDD-phase1 | -0.045\(^{***}\) (0.004) |
| GDD-phase2 | 0.014\(^{**}\) (0.001) |
| KDD-phase2 | -0.163\(^{***}\) (0.003) |
| GDD-phase3 | 0.037\(^{***}\) (0.001) |
| KDD-phase3 | -0.083\(^{***}\) (0.002) |
| Precipitation from planting to mature season | -0.028* (0.001) |
| Year trend | 1.570\(^{**}\) (0.009) |
| Constant | -3.050\(^{***}\) (17.085) |
| Observations | 55735 |
| Number of counties | 2186 |
| R-squared | 0.589 |

Standard errors in parentheses, **\(p < 0.01\), ***\(p < 0.05\), *\(p < 0.1\). The projected daily maximum and minimum temperatures and precipitation data are from the National Aeronautics and Space Administration (NASA) Earth Exchange Global Daily Downscaled Projections (NEX-GDD), which provide results from downsampling exercises applied to results from 21 climate models. These models are derived from the general circulation model (GCM) under the Coupled Model Intercomparison Project Phase 5 (CMIP5). For each model, two scenarios about 21st century pathways of greenhouse gas (GHG) emissions (representative concentration pathway (RCP)’s 4.5 and 8.5) are available. We chose the highest GHG scenario (RCP 8.5) [41] as an upper bound for potential aflatoxin risks in corn in future. The 16 models we considered were listed in the supplementary materials.

Each projected climate data was drawn from models that make different assumptions about the carbon cycle, ocean model, and economic growth. There is insufficient evidence that one model is more reliable than others [42]. Thus, we used a median-climate model (the median model based on precipitation under RCP 8.5: MPI-ESM-LR) as the baseline model. We compare the result with the same model under RCP 4.5, and other 15 models under RCP 8.5.

4. Results
4.1. Predicted growth season in 2031–2040
Figure 1 shows changes in planting dates from the historical average to 2031–2040. The optimal planting dates vary by year and location. In each year/state, the
percentage of regions expected to choose each planting scenario is described in S. table 5. Predicted corn silking stage and dent stage are described in S. tables 3 and 4.

4.2. Predicted weather conditions between 2031 and 2040

Figure 2 compares precipitation and temperature conditions from 2011 to 2020 and 2031 to 2040. Figure 2(a) indicates precipitation changes between these periods AS, while figure 2(b) presents the change AD. A region has a tan color whenever precipitation is expected to decrease in future when compared with 2011–2020, and has a blue color otherwise. Because lower precipitation in AS is associated with higher aflatoxin risk, regions in tan in figure 2(a) are likely to have higher aflatoxin risk in 2031–2040. On the other hand, regions in blue in figure 2(b) are expected to have higher aflatoxin risk, because the area would likely have more rainfall after the dent stage in the future.

Figures 2(c) and (d) represent changes in minimum temperature during AS and AD, respectively. Regions colored in red and orange are expected to have higher minimum temperatures in the future. Higher minimum temperatures can raise time exposure to the temperature range 22 °C–26 °C for both stages. Therefore, these regions are likely to have lower risk in the future. The changes in maximum temperature during AS and AD are described by figures 2(e) and (f) respectively. The impact of higher maximum temperature varies by growing stage. It can increase aflatoxin risk during AS, but reduce the risk during AD if the change affects time exposure to 30 °C and warmer.

4.3. Predicted aflatoxin risk from 2031 to 2040

S. table 6 indicates how many counties are predicted to have increased aflatoxin risk as measured by insurance claims. In 89.5% of counties, the risk is likely to have increased. Specifically, 5.3% of the counties are expected to see risk increase by more than 1%. Distribution of risk is described in figure 3. Figures 3(a) and (b) compare the estimated aflatoxin risks as measured by expected aflatoxin-related insurance claim frequency (%) from 2011 to 2020 and 2031 to 2040, respectively. Historically, aflatoxin-related claims were limited to a few Southern counties. However, our analysis projects that aflatoxin risk will expand toward northern states by 2031–2040. In particular, Kansas and Missouri are projected to have the greatest increase in corn crop aflatoxin occurrences (triggering insurance claims) due to changing climatic conditions. The predicted aflatoxin-related insurance claim (%) by each climate model is described in S. figure 1. Although the predicted risk area is spatially heterogeneous, the overall risks in the northern area are expected to increase.

We estimate future indemnity per premium and then translate this to the total indemnity through multiplying by average premium per county. Each year’s indemnity was converted to 2021 dollars using the consumer price index [5]. Figures 3(c) and (d) compare indemnities from 2011 to 2020 and 2031 to 2040, respectively.
Figure 2. Changes in precipitation, minimum temperature, and maximum temperature (°C) during AS (left) and AD (right). These maps were generated using the median-climate model. (a) Change in the precipitation between two periods (2011–2020 and 2031–2040) during AS. (b) Change in precipitation between these two periods during AD. (c), (d) Change in the minimum temperature between these two periods during AS (left) and AD (right) respectively. (e), (f) Change in the maximum temperature between these two periods during AS (left) and AD (right) respectively. Empty spaces were excluded from the analysis due to lack of data, such as corn planting and temperature.
Figure 3. Predicted aflatoxin risk measured by aflatoxin-related insurance claims per year (%) and aflatoxin-related indemnity (2021 $ value). These maps were generated using the median-climate model. (a) is the aflatoxin-related insurance claims in 2011–2020; (b) is the projected aflatoxin-related insurance claims in 2031–2040; (c) is the aflatoxin-related indemnity amount in 2011–2020; (d) is the projected aflatoxin-related indemnity in 2031–2040. Each county's value is a year-averaged value. Empty spaces were excluded from the analysis due to data unavailability, such as corn planting and temperature.
Table 2. Aflatoxin-related insurance claims and indemnity per year by state. Aflatoxin-related indemnities are calculated by multiplying year-averaged premium per county from each year’s estimated indemnity per premium. The simple mean of each county’s claims (%) was reported. Historical claims and indemnities (2011–2020) are actual data, not projected values.

| States | Aflatoxin-related insurance claims (%) | Aflatoxin-related indemnities ($1000) |
|--------|---------------------------------------|--------------------------------------|
|        | 2011–2020  | 2031–2040 | 2011–2020  | 2031–2040 |
| AL     | 0.02       | 0.06      | 3.1        | 28.7      |
| AR     | 0.04       | 0.14      | 54.9       | 137.6     |
| IL     | 0.03       | 0.28      | 1190.1     | 8626.0    |
| IA     | 0.01       | 0.05      | 150.4      | 1563.9    |
| KS     | 0.14       | 0.99      | 1302.2     | 11764.1   |
| KY     | 0.00       | 0.04      | 20.6       | 153.7     |
| LA     | 0.26       | 0.22      | 63.5       | 127.0     |
| MS     | 0.08       | 0.28      | 151.6      | 457.4     |
| MO     | 0.07       | 0.56      | 638.7      | 4938.2    |
| NE     | 0.00       | 0.04      | 59.9       | 1088.6    |
| NC     | 0.02       | 0.04      | 5.8        | 58.8      |
| OK     | 1.65       | 0.95      | 978.0      | 450.3     |
| TN     | 0.01       | 0.01      | 23.8       | 20.5      |
| TX     | 1.05       | 0.39      | 5563.6     | 2312.7    |
| VA     | 0.00       | 0.02      | 0.5        | 17.4      |
| Average claims | 0.21 | 0.30 | — | — |
| Indemnities | — | — | 10206.6 | 31744.9 |

Table 2 shows expected changes in aflatoxin risk and indemnities by state. The risk of aflatoxin as measured by insurance claims is highly likely to increase in the Corn Belt area. Illinois, Kansas and Missouri are likely to experience high economic losses due to aflatoxin holding all the other conditions such as corn farm land, insurance participation and market price the same. Overall indemnities per year are expected to triple from $10 million to $31 million, especially in the Central Great Plains and southern portions of the Western Corn Belt. To estimate real economic loss from indemnity, we used a mark-up range. Yu et al. suggested to estimate economic loss by multiplying mark-up range (1.43–2) from indemnity amount assuming that uninsured areas have the same possibility for incidence of aflatoxin within an insured area [34]. It was found that changes in losses are expected to amount to between $45 million and $63 million per year. Given that the total indemnity amount for corn is $2.6 billion in 2020 [43], the estimated loss, which is approximately 4% of the total indemnity, is significant from a single-cause standpoint.

5. Discussion

Aflatoxin has been linked to many harmful health effects in humans and animals, and is most common in corn grown in warm climates. Although to date, the US Corn Belt—a major supplier of corn not just to the US, but worldwide—has rarely had severe aflatoxin contamination events, this may change in the near future; as near-term projected climatic conditions favor fungal infection and aflatoxin accumulation. This could have implications for global food security, as the US provides well over half of the supply of corn traded globally [44]. Increased aflatoxin exposure is linked to increased liver cancer risk in humans [16], and field corn produced in the US is in part used for human food both in the US and worldwide. Additionally, increased aflatoxin in dairy animal feed is linked to higher levels of a metabolite aflatoxin M1 in milk [45], which—although not associated with significant human cancer risk [46]—may nonetheless cause toxicological effects not yet elucidated.

This study provides an empirical response model of aflatoxin risk in corn from climate change across 15 major corn-planting states in the US. Our analysis allows for one of the most readily enacted agronomic practice adaptations to climate change, through altering planting date. Another novelty in the framework is the partition of weather exposures based on corn growing stages. This method can be modified for application to other crops that are exposed to weather-triggered mycotoxin accumulations such as peanuts; also very vulnerable to aflatoxin contamination.

Severe aflatoxin contamination of corn is a major concern for the future. The results of this study suggest that aflatoxin-related risk will increase overall in the US due to climate change. Even though aflatoxin events are currently largely confined to southern states, prevalence will eventually shift to the Corn Belt. This shift may lead to disruptions in domestic and global corn markets by increasing the expected economic impact. In the US, aflatoxin is regulated by the Food and Drug Administration in corn intended for both human food and animal feed, so health risks have generally been low; the primary loss is to corn growers from rejected lots with excessive aflatoxin.
levels. But in the future, if corn grown throughout the US has higher aflatoxin levels, clean corn may be in shorter supply, meaning economic losses to growers and potential costs throughout the supply chain, including to consumers. Additionally, exported corn may be subject to a country’s regulatory standards for aflatoxin; or in the absence of such standards, countries may import relatively more contaminated corn, with potential human and animal health effects. Even if regulatory standards for aflatoxin exist and are enforced in the US and elsewhere, having relatively more aflatoxin in food and feed in near-future climatic conditions (even if still below limits) must increase health risks, as aflatoxin is a known carcinogen.

Therefore, there is a critical need to plan to mitigate aflatoxin risk under future climate conditions to preserve a safe food supply in the US and worldwide. Irrigation may be one important strategy for reducing aflatoxin risk, by reducing drought-related stress on corn that predisposes it to fungal infection [29]. Agricultural biotechnologies such as biocontrol, transgenic or gene-edited corn, and RNA interference (RNAi) corn for host-induced gene silencing of aflatoxin biosynthesis can also be effective tools [34, 47, 48]. Adoption of cultural and genetic approaches that have been used for decades, including plant breeding using conventional and transgenic methods, may also help to reduce aflatoxin risk in the future.

There are several key limitations to this study, and these indicate areas for future research. We have assumed that all growing conditions except climate and growth seasons are the same between 2011–2020 and 2031–2040. However, grower strategies beyond shifting planting dates may also affect future aflatoxin risk; new seeds and technologies may become available in the interim that can afford better aflatoxin control. Also, the effect of CO$_2$ on aflatoxin needs to be included in our model because elevated CO$_2$ due to climate change affect aflatoxin through both crop and toxin production [15, 49]. Moreover, our analyses focused on US counties that currently plant and have historically planted relatively large amounts of corn. However, other counties and states may produce more corn in the future, in part due to shifting climate conditions. Indeed, climate change may cause a geographical shift in what is considered the ‘Corn Belt’ region of the United States [50]. These are interesting considerations for future studies on the topic of corn production and food safety in the face of climate change.

**Data availability statement**

Historic daily temperatures and precipitation data are available at www.columbia.edu/ws2162/links.html and http://prism.oregonstate.edu. Projected temperature and precipitation data are available at https://cds.nccs.nasa.gov/nex-gddp/. Insurance data are available at www.rma.usda.gov/data. Irrigation and crop progress data are available at https://water.usgs.gov/watuse/data/ and https://quickstats.nass.usda.gov/ respectively.

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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**Author contributions**

J Y collected and analyzed data, contributed to research design, and wrote the paper; J T collected data and wrote the paper; F W and D A H designed the research and wrote the paper. All authors discussed the results and commented on the manuscript.

**Conflict of interest**

The authors declare no competing interests.

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