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Evaluating Risk of Aflatoxin Field Contamination from Climate Change Using New Modules inside DSSAT

Timothy S. Thomas, Richard Robertson, and Kenneth Boote

Abstract

Aflatoxins affect the health of close to 70 percent of the population of the world through contaminated food. Smallholder farmers in developing countries can be especially hard hit, since they consume a high proportion of what they produce without a clear knowledge of the level of contamination their harvest might have. Climate change can cause dramatic shifts in the level of contamination and the frequency of that high levels of aflatoxins are found in harvested foods, particularly maize and groundnuts. In this paper, we introduce new software that is able to estimate potential field concentrations of aflatoxins based on weather, and then apply the software to the question of how projected changes in climate will affect the occurrence of aflatoxins in six countries. The analysis is done at a very fine geographic resolution so that problem areas within countries are also identified.

For rainfed groundnuts, baseline period calculations using the module show fairly high frequency of expected contamination levels above 4 ppb for Burkina Faso and Niger (39 and 56 percent), while Nigeria has a more modest estimate of 14 percent. However, factoring in climate change, we find great variation in projections. One of the five climate models used in the analysis projects a much wetter region which serves to drive down aflatoxin concentrations steeply. However, others have lower or even negative projections for changes in rainfall and coupled with temperature increases (large in some climate models), three of the five climate models project rising aflatoxin concentrations.

The frequency of projected contamination levels above 4 ppb in rainfed maize are high in the baseline for Niger, at 43 percent, though Niger grows little maize. Burkina Faso, Nigeria, Guatemala, and Honduras all have more modest projections in the baseline (8, 9, 4, 10), while Nepal has just a trace above 0. Aflatoxin concentrations are projected to rise with climate change by all 5 models for Nepal, Guatemala, Honduras, and Nigeria, but only rise for 3 models for Niger and 4 of the 5 models for Burkina Faso.

We use regressions with weather variables on projected aflatoxin concentrations levels above 4 ppb to better understand critical levels of rainfall and temperature that could trigger local crises with aflatoxins in on-farm consumption of harvested foods. At the end of the paper, we examine why aflatoxin concentrations in Nepal as reported by the modeling results appear low despite aflatoxins being a significant issue for the country.

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Introduction

Aflatoxins are fungal metabolites mainly produced by *Aspergillus flavus* and *Aspergillus parasiticus*. They are found naturally in agricultural fields, but often at low levels. In the right weather conditions – usually involving some kind of stress on the plant such as drought in combination with elevated temperatures, the levels can grow and can cause health issues when the harvest is consumed by humans. Insect damage with these conditions can also contribute to higher levels of aflatoxin concentration.

Sanders et al. (1985) reported that for groundnuts, the conditions conducive to pre-harvest contamination of aflatoxins are 20 to 30 days of drought stress with soil temperatures between 28 and 30.5^0C. In addition to field contamination, fungi producing the aflatoxins can also grow and flourish in crops that are stored.

Aflatoxins affect the safety of food in many countries. This is especially true for tropical and sub-tropical countries but also impacts farmers in temperate countries during the warm growing season when there is water stress. Seventy percent of the world's population are exposed to high levels of aflatoxins (Brown 2018).

Aflatoxin exposure has been associated with childhood stunting, which in turn is associated with vulnerability to infectious diseases and cognitive impairment lasting beyond childhood. Exposure can lead to liver cancer, and at very high concentrations, can lead to death shortly after consumption. One of the problems with aflatoxins is that they are not destroyed in heat treatments of cooking processes or milk treatment processes.

While livestock are able to consume crops that have a higher level of contamination than humans can safely ingest, high levels of aflatoxin contamination affect animal health, rate of growth, and productivity. Aflatoxins are passed through cows into the milk thereby affecting people who consume milk.

It has been argued that aflatoxin contamination prevents African farmers from exporting peanut and other crops to the United States and Europe, though it may be more of an issue of quality of grain produced and insufficient surplus to sell.

In this paper, we focus on field contamination rather than contamination of foods while in storage, though the latter is also a very important topic for food safety. We employ two new modules inside the crop simulation software package DSSAT: one module for aflatoxins in groundnuts and the other for aflatoxins in maize. These modules were developed by a team from the University of Florida and then tested by another team from IFPRI with the support of University of Florida researchers. We were asked to focus on 5 countries: Niger, Burkina Faso, Nepal, Guatemala, and Honduras. In the middle of the analysis, a request was made to also evaluate aflatoxins in Nigeria, and the team was able to comply.

Our immediate goal is to evaluate the likely impact of climate change on aflatoxin concentrations in these six countries, within the broader goal of being able to evaluate the impact of weather on the risk of aflatoxin contamination. A future goal is to better calibrate the models so that they can be used to serve as an early warning tool for aflatoxin hotspots.

Data and Methodology

The Decision Support System for Agrotechnology Transfer (DSSAT) is crop simulation software package consisting of multiple mathematical models (Jones et al. 2003). It is recognized as one of the most accurate models for biophysical analysis of crop growth. It is calibrated to compute yields for 30 different crops given soil, weather, and farm management information.

For this analysis, we ran the model for separate data at each pixel (every 5 arc-minutes, which is roughly 9 kilometers at the equator). The models “grow” the crop in daily time increments using DSSAT’s weather simulator and the monthly weather statistics that WorldClim 1.4 (Hijmans et al. 2005) and the climate models provide. We created 40 different years of plausible weather at each pixel for each climate.

The soil data used were adapted by Koo and Dimes (2010) from the Harmonized World Soil Data Base by Batjes et al. (2009). The soil data were simplified into 27 soil types, each with high, medium, or low soil organic carbon; deep, medium, or shallow rooting depth; and a major component of sand, loam, or clay. When grid-cells had more than one soil type represented, the dominant type was used.

We not only calculated yields for each pixel, we computed them over a window of possible planting dates, looking for the most optimal planting date. When we found the planting date that gave the best yield, we recorded the percentage of years associated with that planting date and pixel that the aflatoxin concentrations computed by the new DSSAT aflatoxin modules were over 4 parts per billion.

To get national and subnational values for aflatoxin frequencies, we computed a weighted average of the frequency of critical aflatoxin levels at the pixel level using the weights provided by the harvested area of the pixel for that particular crop, given by You et al. (2014). The analysis was not embedded within an economic model, so the harvested area in each pixel was held constant over time.

The peanut aflatoxin module is designed so that the prediction of aflatoxin contamination is highly dependent on the prediction of soil temperature, crop water stress, and pod-zone soil water status. The maize aflatoxin module is set so that the prediction of aflatoxin contamination is highly dependent on air temperature and predicted crop water stress.

We use these modules to examine not only the projected levels of aflatoxins under the baseline period of 1960-1990, but also under future scenarios with climate change. We use 5 GCMs that were used as part of the AgMIP GGCMI work (Rosenzweig et al. 2014; Muller and Robertson 2014). We apply them to six countries in three continents: Nigeria, Niger, and Burkina Faso, for which we employ both crop modules; and Guatemala, Honduras, and Nepal, for which we employ only the rainfed maize aflatoxin module (since peanuts are a minor crop in these countries).

Figure 1 shows where rainfed groundnuts and rainfed maize are grown in Nigeria, Niger, and Burkina Faso. These provide weights for the tabulated changes in aflatoxin levels due to climate change later in this report. We note that very little groundnut is grown in southern Nigeria, and the locations for growth of groundnut are dispersed throughout southern Niger and central and western Burkina Faso. The densest concentration of groundnut cultivation is in Kano state in Nigeria. Little rainfed maize is grown in Niger and the northern-most part of Nigeria, and in Burkina Faso it is concentrated in the west. Rainfed maize grows throughout most of the rest of Nigeria.

Figure 2 shows where rainfed maize is grown in Guatemala and Honduras. It appears much more concentrated in Guatemala, with most of it located south of Petén and east of Izabal and Zacapa. Rainfed maize is grown throughout Honduras, except in the eastern-most department of Gracias a Dios.

Figure 3 shows the location of rainfed maize cultivation in Nepal. It tends to be located in the central portion of the country and in the western part of the southern border with India.

Results

West Africa: Nigeria, Niger, and Burkina Faso

Figure 4 shows the results of using the DSSAT aflatoxin modules on the climate of 1960 to 1990, which is based on the data in WorldClim 1.4 (Hijmans et al. 2005) and is considered the baseline period from which climate change is measured against. For rainfed groundnuts, we see very high concentrations in northeastern Burkina Faso and western Niger, and only slightly lower concentrations extending eastward across Niger to the border with Chad. There are also pockets in northernmost Nigeria. Some of the highest zones of aflatoxin contamination are areas where few rainfed groundnuts are grown (compare to Figure 1). However, there are some places with high aflatoxin levels that also have high levels of groundnut cultivation.

Figure 4 shows a similar pattern of aflatoxins with rainfed maize, though they tend to be less concentrated in western Niger and eastern Burkina Faso, and more in the central and eastern crop zones of Niger. In fact, compare this figure with Figure 1, we see that high rainfed maize cultivation areas are in lower to moderate aflatoxin levels than was true of rainfed groundnuts.

Figure 5 shows the rainfall levels during the 4-month period that begins with the planting month (which was calculated based on the date at each point that gave the highest yield as calculated in DSSAT). There is a general trend for rainfall levels to decrease from south to north. Central Nigeria is an exception, with a portion of high rainfall extending upward into that area, with lower rainfall levels on both the east and west. Comparing to Figure 1, rainfed maize cultivation area seems to be lower in areas below 600 millimeters during the growing season and is definitely less in areas below 450 millimeters during the growing season. We can similarly infer that rainfed groundnuts seem to prefer at least 300 millimeters of rain during the growing season.

Figure 6 shows the mean daily maximum temperature for the warmest month of the 4-month period that begins with the planting month. There is an increase in temperature moving from south to north, but the gradient is less pronounced than it was for rainfall in much of Nigeria. For the bulk of Nigeria we note a mean daily maximum temperatures during the growing season that are below 32 degrees C. While Burkina Faso has a fairly large percentage of their growing area for rainfed maize in places that have their mean daily maximum temperature of the warmest month up to 34 degrees C, much of the growing area for rainfed groundnuts in Burkina Faso and Niger are areas that go up to 37 degrees C for their mean daily maximum temperature.

Figure 7 shows the projected changes in the first four months of the growing season rainfall for the five climate models used in this analysis. These models were from the AgMIP GGCMI (Rosenzweig et al. 2014) and are from the suite of CMIP5 models that were part of the IPCC's Fifth Assessment report that was published in 2013. The models assume the high emissions scenario, RCP 8.5. The GFDL climate model projects a drier climate over the three countries, while except for a small area in the extreme south of Nigeria, the MIROC climate model projects a vastly wetter growing season. There appear to be similarities between the HadGEM, IPSL, and NorES model, with wetter areas spanning most of the northern portion of the study area, and drier areas in part of the southern portion of the study area.

Figure 8 shows the mean daily maximum temperature of the warmest month of the 4-month growing period for rainfed maize. Projected temperature changes are lowest in the NorES and GFDL climate models. HadGEM and IPSL are very similar, with 3-4 degree Celsius changes across much of the northern part of the study area, and 2-3 degree changes in the south. The MIROC model has highly spatially specific changes, with some areas actually projected to cool down, while other areas heating up greatly.

Figure 9 shows the projected percentage point change in aflatoxin concentration for rainfed groundnuts for the median and each of the 5 climate models used in this study, as projected at each pixel. Table 1 summarizes the results by country. We see that in the baseline climate of 1960 to 1990, Nigeria typically is projected to have had modest aflatoxin contamination, with 14 percent of cultivated area above 4 ppb in a typical year, while Burkina Faso is projected to have had 39 percent and Niger 56 percent. Nigeria has a much higher groundnut acreage, according to SPAM data (You et al. 2014).

Table 1 also shows great variation of climate effects between climate models. MIROC and NorES consistently show reductions in aflatoxin concentration, while the other three show increases, with GFDL the worst, followed by IPSL. The MIROC results are driven by the projected large increases in precipitation, while those for NorES are due to modest increases in precipitation in the north coupled with modest increases in temperature. GFDL projects less rainfall, which is the main cause of rising aflatoxin concentrations, while the IPSL and HadGEM increases in aflatoxins are driven by large temperature increases. Details of changes in aflatoxin concentrations can be seen in Figure 9. MIROC and NorES have large areas in Burkina Faso and Niger that are projected to have lower aflatoxin concentrations with climate change. We also see that large portions of Niger and northern Nigeria are to become much higher with climate change. Generally, though, most of Nigeria has very little change in aflatoxin levels projected with any of the five climate models.

Appendix Figure 1 shows the states and local government areas (LGAs) for Nigeria, as well as the USAID Feed the Future (FTF) Zones of Influence (ZoIs). The ZoIs are selected administrative units for special focus in each country. For the case of Nigeria, they are selected at the LGA level. Using these, we tabulate groundnut aflatoxin concentrations as simulated by the DSSAT aflatoxin module for Nigeria's states and ZoIs and place the results in Appendix Tables 1 and 2.

Appendix Figure 2 shows the departments and communes for Niger, along with the FTF ZoI. We use these to tabulate the aflatoxin frequencies for Niger in Appendix Tables 3 and 4. Similarly, Appendix Figure 3 shows the regions and provinces of Burkina Faso. Appendix Table 5 presents the groundnut aflatoxin frequencies by region and province.

Figure 10 shows the projected percentage point change in aflatoxin concentration for rainfed maize at the pixel level for the median and each of the 5 climate models used in this study. Table 2 summarizes the results by country, including three countries included in the analysis for which the detailed results and discussion will be presented later in this report.

From Table 2, we see that in the baseline period, Niger has very little rainfed maize but very high aflatoxin contamination frequency above 4 ppb for the rainfed maize it does produce. On the other hand, Nigeria and Burkina Faso have low contamination frequencies of 9 and 8 percent. However, with climate change, all 5 climate models show an increase in aflatoxin frequency in Nigeria, and 4 of the 5 models show it for Burkina Faso, while 3 of the 5 show it for Niger. Under the MIROC model, which has increased rainfall but only a modest increase in temperature, aflatoxin occurrences are projected to become quite low in both Niger and Burkina Faso.

Figure 10 shows vastly different projections for the effects of different climate models on aflatoxin contamination frequencies, though it is important to keep in mind that the strongest differences appear in Niger, which has very little rainfed maize. MIROC, for example, shows a geographically broad reduction in aflatoxins, spanning from Burkina Faso through Niger and into northern Nigeria. The pattern for aflatoxin reduction is similar for the NorES climate model, though the effects are much weaker. On the other hand, the GFDL model shows a strong increase in aflatoxin frequency in about the same areas as we saw the decrease in the MIROC model.

Geographically refining the rainfed maize aflatoxin tabulations, Appendix Tables 6 and 7 show aflatoxin frequencies for Nigeria's states and ZoIs. Appendix Tables 8 and 9 show rainfed maize aflatoxin frequencies for Niger's regions and departments, and for its ZoIs. Appendix Table 10 presents the rainfed maize aflatoxin frequencies for the regions and provinces of Burkina Faso.

Central America: Guatemala and Honduras

Figure 11 shows the baseline rainfed maize aflatoxin frequencies projected for the two Central American countries in our study – Guatemala and Honduras – using the DSSAT aflatoxin module and the climate of the 1960-1990 period. We see that generally speaking, there are low aflatoxin levels throughout most of both countries, though some high levels in the north of Guatemala and in a patch spanning Zacapa and El Progresso, and then two patches along the Caribbean coast in Colón and Cortés in Honduras. Most of these high aflatoxin areas are not big rainfed maize areas, though some are, such as El Progresso (see Figure 2).

Figure 12 shows that many of these high aflatoxin levels are lower rainfall levels for this region, ranging from 450 to 600 millimeters during the 4-month period we count as part of the growing season for rainfed maize. We also see from Figure 13 that these areas tend to warmer areas relative to the rest of the region, often with mean daily maximum temperatures of the warmest month being above 32 degrees C.

Figure 14 shows how the rainfall is projected to change by 2050 during the growing season. The GFDL climate model projects a high increase in rainfall, while the other 4 climate models generally project a decline in rainfall during the growing season. IPSL appears to have the lowest rainfall out of the five.

Figure 15 shows projections for changes in the mean daily maximum temperature for the warmest month of the 4-month growing period. We note that the highest increases are found in the HadGEM model, with only modest increases in the GFDL and NorES models.

Figure 16 shows the projected percentage point changes to the two countries in our study from the Central American region. One of the most visible spots showing increases in aflatoxin frequencies is the northern part of Guatemala in Petén. It is important to note that there is very little rainfed maize currently grown there. We also note that much of the rest of the country has little change in aflatoxin, while a higher percentage of Honduras has growth in aflatoxins. Gracias a Dios has a reduction in aflatoxins projected, though it grows very little rainfed maize. We can see in the GFDL model that there is very little change projected in aflatoxin

Table 2 shows that the aflatoxin levels of both countries are projected to rise under climate change, with the aflatoxin frequency in Guatemala from 4.5 percent to anywhere from 6.0 percent to 28.8 percent. Honduras has an even larger projected rise, from 9.5 percent to anywhere from 11.4 percent to 46.1 percent, with the second smallest at 33.2 percent.

Appendix Figure 4 shows the departments and municipalities of Guatemala, along with the municipalities that have been selected as Feed the Future Zones of Influence. Appendix Table 11 tabulates those results. Appendix Figure 5 shows the departments and municipalities of Honduras. Appendix Table 12 shows the predicted aflatoxin frequencies by department in Honduras.

South Asia: Nepal

Figure 17 shows the projections for rainfed maize aflatoxin frequency during the climate of 1960-1990 in Nepal. As can be readily seen both here and in Table 2 is that the projections for occurrence of aflatoxins in the field from the analysis using the DSSAT module is very low across the country, at 0.2 percent. However, aflatoxin levels are reported to be much higher in Nepal. Mitchell, Riley, Egner, et al. (2016) show that the aflatoxin levels in children computed in their study in Nepal were similar to those of African nations. Later in this paper, we examine what might be leading to low predictions from the model.

Figure 18 shows the rainfall levels of the growing season for the baseline period of 1960 to 1990. Most of the rainfed maize growing area identified in Figure 3 lies in areas with abundant rainfall. Figure 19 shows the mean daily maximum temperature of the warmest month during the 4-month growing period for rainfed maize. In the rainfed maize growing areas, this value seems to range from 30 to 34 degrees.

In Figure 20, we see projected changes in growing season rainfall for 5 climate models between the baseline period and 2050. Three models – IPSL, MIROC, and NorES – show precipitation levels rising across the entire country. GFDL, on the other hand, shows significant lowering of rainfall in the southern portion of the eastern part of the country. Figure 3 shows that rainfed maize is grown there. HadGEM shows that there will be a more modest decline in rainfall, but this time in the northern portion of the eastern part of the country, where very little rainfed maize is grown.

Figure 21 shows projected changes in the mean daily maximum temperature of the warmest month of the growing period. The models differ in their projections for level of change and location of change. Three of the models show portions that are projected to have greater than 4^0C increases in temperature, and 2 of the models have large areas that are only projected to warm by 1-2^0C.

Figure 22 shows changes in aflatoxin frequencies due to climate change. Very little change is noted in any of the maps in the figure, however the change in the GFDL climate model – which projects lower rainfall in an important location in which rainfed maize is grown -- gives the largest projected increase for the nation, as summarized in Table 2.

Evaluating drivers of aflatoxins from DSSAT model

Rainfed groundnuts

Using the total rainfall during the growing period, which we assumed to be a 4-month period from the planting month to the third month afterward, along with the mean daily maximum temperature for the warmest month during that period, we regressed these values and their square on the average fraction of years that groundnut aflatoxin levels are higher than 4 ppb.[1] The results are found in Table 3, and the effects of each weather variable are graphed in Figure 23. The temperature and precipitation ranges in the graphs reflect roughly the ranges of the data from the 5th to the 95th percentiles.

First, we note that above 800 to 900 millimeters of rainfall during the 4-months of the growing season, there is very little probability of aflatoxins to appear in the crop as it is harvested in the field. Second, we note that aflatoxin contamination is very high for low rainfall, being at least 80 percent for all temperatures in the range observed in the data. Third, we note that the probability of aflatoxin contamination declines steeply between 200 millimeters of rain and around 500 to 600 millimeters. Fourth, we see that there tend to be lower predicted aflatoxin levels in cooler climates, with aflatoxin levels peaking at around 36 to 37 degrees Celsius for daily maximum temperature.

Rainfed maize

We did a similar analysis for rainfed maize aflatoxins as we did for groundnut aflatoxins. One of the main differences was that the rainfed maize analysis covered a more diverse area. In addition to Nigeria, Niger, and Burkina Faso, it also included Guatemala, Honduras, and Nepal. We found it important to include elevation as an explanatory variable, along with the soil types that were used in the crop modeling. We examined the explanatory power of soils and elevation in the groundnut analysis but found that they added very little in their ability to explain groundnut aflatoxin levels.

One difference we had with rainfed maize is that we used climate variables based on a 3-month growing season instead of a 4-month growing season. This is not because the rainfed maize growing season does not span at least 4 months, but because the explanatory power of the 3-month climate aggregates was significantly better than the 4-month aggregate.

In a separate regression not published here, we found that the second month rainfall and temperature (the month after the growing month) had even stronger explanatory power than the 3-month aggregates, and very little was added by including monthly data from the first, third, and fourth months. This suggests that if the aflatoxin module is reasonably reflecting real-life processes in how aflatoxins are produced in rainfed maize, then there is a key opportunity to establish an early warning system 2 to 3 months prior to harvest, based on the weather of the second month of the growing period. The reason for this is that the period with lack of rainfall typically precedes crop water deficit by 1-2 weeks (the time required for evapotranspiration to deplete a typical soil profile to arrive at serious water

[1] We "logitized" the dependent variable in the regression, frac, using the following formula: lgtfrac = ln(.001+frac) - ln(1.001-frac). We did this to put a bound on the predicted values of frac to range between 0 and 1 (0 percent to 100 percent). The additional fraction of 0.001 was incorporated to allow us to use values of frac equal to either 0 or 1.

deficit), and there is a key phase in rainfed maize growth that takes place during the third month. Soil type in the analysis is a factor that determines onset and degree of crop water stress.

Results of the analysis of drivers of aflatoxin contamination in rainfed maize are found in Table 4. The effects of each weather variable are graphed in Figure 24. As for case of rainfed groundnuts, the temperature and precipitation ranges in the graphs reflect roughly the ranges of the data from the 5th to the 95th percentiles observed for rainfed maize in the areas of the countries used in the regression.

Figure 24 shows the effect of precipitation and temperature on aflatoxins in rainfed maize. At low levels of rainfall, aflatoxin concentrations can vary greatly depending upon the temperature. Very low levels of aflatoxins are projected above 800 to 900 millimeters of rainfall in the 3-month period. Except for very low levels of rainfall, there is less chance of aflatoxin contamination below 26 degrees C.

Figure 25 shows how the type of soil affects how precipitation and temperature affect the presence of aflatoxins. Just considering the major soils in the study area, at lower levels of rainfall, the soil type can lead to more than a 20-percentage point difference in aflatoxin levels. At high temperatures, the soil type can lead to more than a 35-percentage point difference in aflatoxin levels. The primary avenue through which the soils are affecting aflatoxin levels is in water retention effects on computed crop water deficit. Without enough moisture in the soil, plants become stressed and susceptible to aflatoxins.

Explaining the low predictions for Nepal

As mentioned previously, Mitchell, Riley, Egner, et al. (2016) show that the aflatoxin levels in children computed in their study in Nepal were similar to those of African nations, and yet the baseline rainfed maize aflatoxin levels for Nepal are near zero in our analysis. Flach (1987) reports that Karmacharya (1984) found that the aflatoxin content of rainfed maize at harvest is low but can be quite high in stored rainfed maize and in rainfed maize flour. That is, the contamination in Nepal appears to enter primarily post-harvest, or at least did back when the study was done. We were unable to find more recent published results on field contamination in Nepal.

However, using AgMERRA data from 1980-2010, we ran a regression of annual precipitation on year, in order to see if there was a trend in how rainfall has been changing. What we found for Nepal is in Figure 26, which shows much of the eastern part of the country, which is where some of the rainfed maize is grown, has trended to be lower in annual rainfall by 350 to 500 millimeters a year. Even in the central part of the country, rainfall has declined by 100 to 200 millimeters per year. As Figure 24 shows, lower rainfall leads to a higher frequency of aflatoxin occurrence.

As we noted in Figure 20, the GFDL climate model predicted a large rainfall reduction in the southern part of the eastern region, where an important portion of the rainfed maize is grown. This change mimics that seen in Figure 26, except Figure 26 has a reduction in an even larger portion of the country. In Table 2, we see that aflatoxins for GFDL are projected at 7.2 percent. This suggests that if we had modeled the lower rainfall and higher temperatures that Nepal seems to have been experiencing in recent decades, the aflatoxin frequencies calculated by DSSAT would more closely mimic those measured in the field during that time.

Using the same dataset that we used to generate Figure 26, we computed temperature trends over the same 30-year period and show the results in Figure 27. Temperature has trended upward in most of

Nepal, and most strongly in the central part where much of the rainfed maize is grown. As Figure 24 also shows, higher temperatures lead to higher aflatoxins, reinforcing the idea that over the past couple decades, both precipitation and temperature have trended in such a way as to rapidly increase aflatoxins in rainfed maize in the field in Nepal.

While the analysis in Figures 26 and 27 used annual data, the reason that it is applicable to our analysis, at least for the sake of looking at trends, is that the warmest month of the year will be in the growing season, and much of the precipitation will be in the growing season.

This analysis of recent climate trends together with our analysis of how weather influences field contamination of rainfed maize with aflatoxins tells us that in the past field contamination may have been low, but more recently, the field contamination levels are likely higher, since the weather prior to 1990 was wetter and cooler, providing an environment that is not conducive to aflatoxin contamination.

It also shows us the potential of the DSSAT aflatoxin module to identify potential future hotspots due to climate change, and with some further testing, to create alerts for farmers and government officials as to when the temperature and precipitation of the growing season creates the conditions for an outbreak of aflatoxin contamination.

Conclusions

In this study, we applied two new aflatoxin modules – one for rainfed maize and the other for rainfed groundnuts – to six countries. We calculated the frequency at which the harvests would have aflatoxin levels above 4 ppb, and then we compared those results to what aflatoxin levels would be projected for each of five GCMs from the AgMIP GGCMI. We did the calculations at pixel level and noted areas of both increase and decrease, and noted some conflicting projections between climate models.

In order to better understand how changes in growing season precipitation and mean daily maximum temperature for the warmest month affect aflatoxin frequency, we recovered the projections from the new DSSAT modules at the pixel level for the 6 countries and ran regressions on them. The regressions clearly showed how water stress greatly increases the frequency of critical aflatoxin concentration, and that after a certain level of rainfall, there is little risk of aflatoxins.

The regression showed some responsiveness of rainfed groundnuts to temperature change, though this was not consistent for all levels of precipitation. But the regression on rainfed maize aflatoxins showed a clear response of aflatoxins to higher temperatures.

The very low projections for rainfed maize aflatoxins in Nepal fly in the face of an awareness that they are a serious health problem there, but which was not well-known until recently. We did some analysis on climate trends in Nepal, and discovered a noteworthy decline in annual rainfall there between 1980 and 2010, and an increase in mean daily maximum temperature there over the same years. Since the baseline data was for the 1960 to 1990 period, it is conceivable that there was not a problem there previously, but as a result of climate change in Nepal, there is one now. The climate models tended to project more rainfall rather than less, so that is why they generally did not project an increase in aflatoxins with climate change. However, there was an area of significant drying in the GFDL model, and this drying happened to occur in a rainfed maize-growing area, and the rise in aflatoxins for the country in that climate model shows up in the tables. This brings up a question of which GCM scenarios are correct.

We also noticed that for rainfed maize, a shortage of rainfall in days 30 to 60 after sowing might be an excellent early warning for a possible aflatoxin outbreak or hotspot by harvest time. But this also suggests that supplemental watering during that time might also be a good solution when it is feasible.

Recommendations

What can a country do if it is facing significant problems with aflatoxin contamination either now or in the future? There are a number of suggestions. First, one of the easiest to implement, if it is feasible, is to switch planting months if the yields are not too adversely affected but the aflatoxin concentrations might be reduced.

Second, in places where it is possible, apply water to the crop during the driest times. While the literature suggests that this might be shortly before harvest, our regression analysis on the model suggested it might be during the period after planting (days 30 to 60). Improving water retention would be a good long-term strategy, perhaps through bunds or investing in improving soil organic matter.

Another idea is to use biocontrol, which involves introducing non-harmful fungi to out-compete bad aflatoxins. The effect lingers for more than one season and potentially helps neighbors. But this requires more technology in growing out the new fungi and applying it to the fields at the start of the season before a problem is known.

Some studies have found that liming soils reduces aflatoxins.

Since aflatoxin contamination is worse when crops are damaged by insects, techniques to reduce their effect can be very helpful.

There has not been great success in developing aflatoxin resistant varieties, but perhaps with new breeding techniques that have been put into practice recently, there is more hope now than ever. Some small successes are likely to be associated with creating more drought-tolerant cultivars, especially those that are more deeply rooted to sustain water uptake longer into drought periods

While this would involve significant behavioral change – since smallholder farmers tend to consume much of what they produce – switching to different crops that do not have significant aflatoxin problems should be considered as an option to be presented to farmers.

New faster testing for aflatoxin contamination could be developed so that farmers would know whether they have a problem post-harvest. Even if the levels of contamination make the crop unfit for human consumption, there are alternative uses that would still keep the farmer from experiencing a total loss. For example, infected peanuts can still be used for peanut oil, since filtration removes most of the contamination. And it is possible to use infected crops in livestock feed that are treated with "clay-type" binding agents or decontaminated with ammoniation.

Finally, care could be taken to make a number of improvements to harvesting, processing, drying, and storage practices, to reduce the concentration in stored products prior to human consumption. These particularly include appropriate drying of the crops after harvest.

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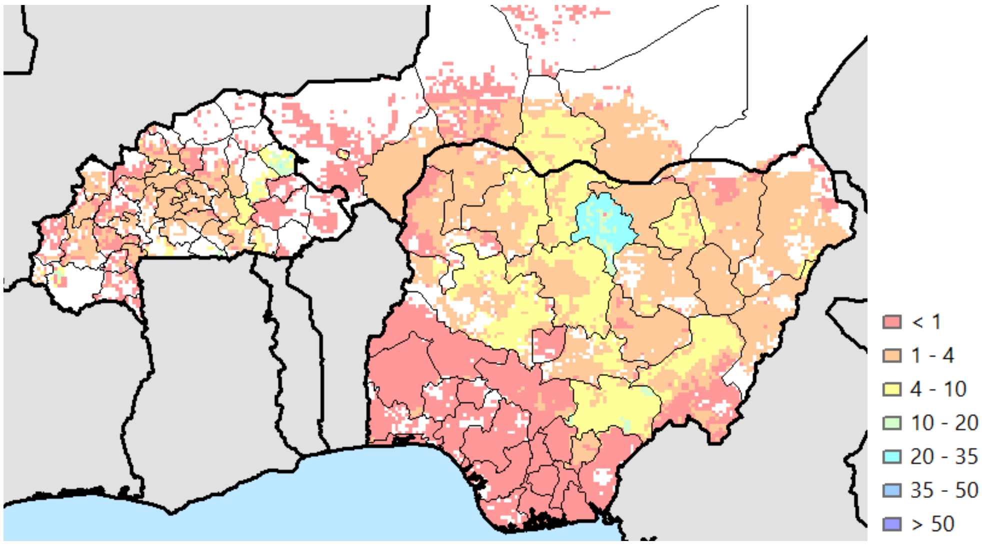
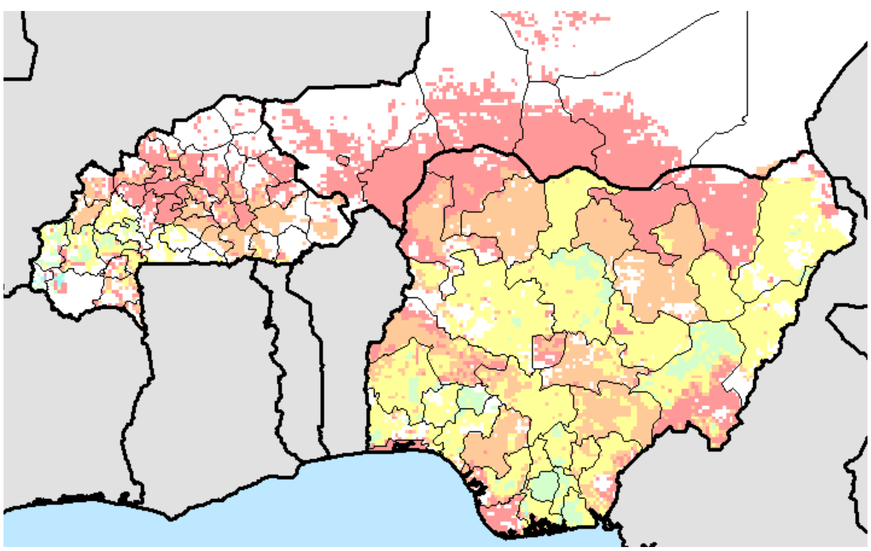
Figures and Tables

Figure 1. Extent of land in rainfed maize and rainfed groundnuts in Nigeria, Niger, and Burkina Faso (percent of land in pixel)

Rainfed groundnuts

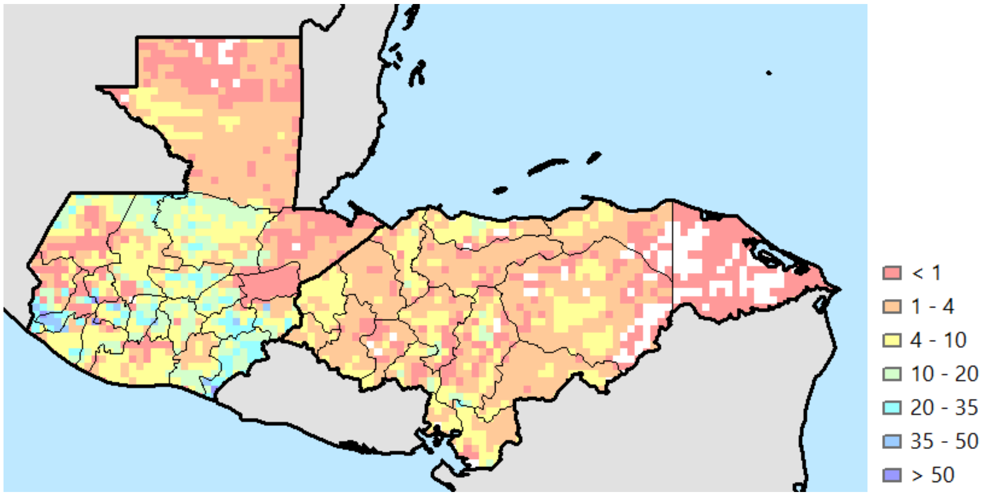


Rainfed maize



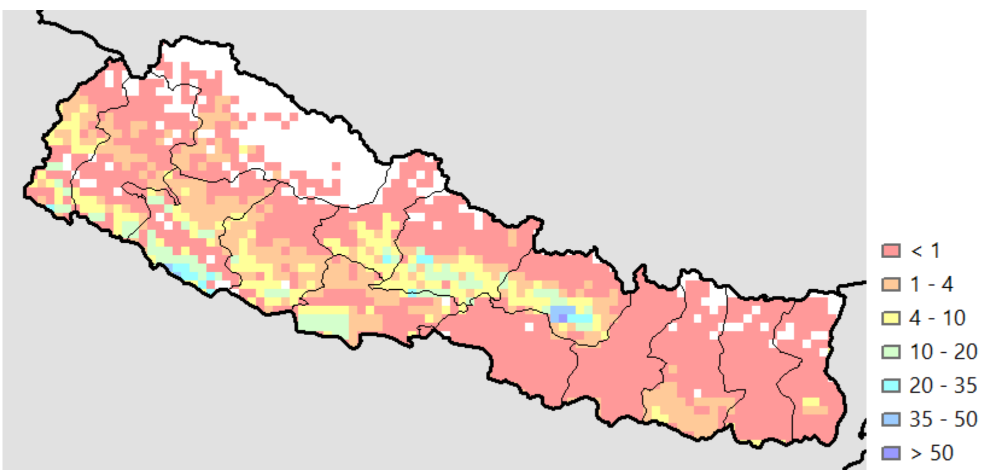
Source: SPAM (You et al. 2014).

Figure 2. Extent of land in rainfed maize in Guatemala and Honduras (percent of land in pixel)



Source: SPAM (You et al. 2014).

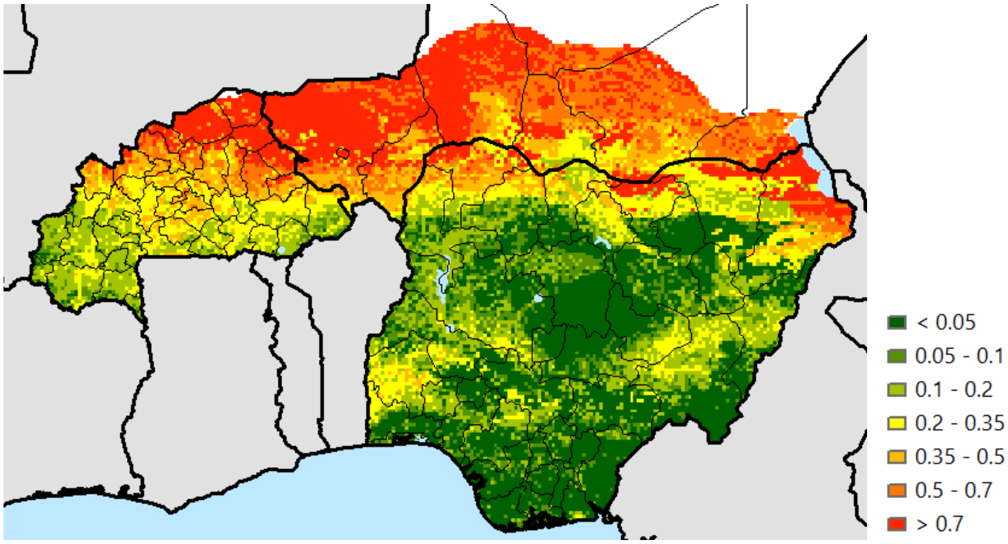
Figure 3. Extent of land in rainfed maize in Nepal (percent of land in pixel)



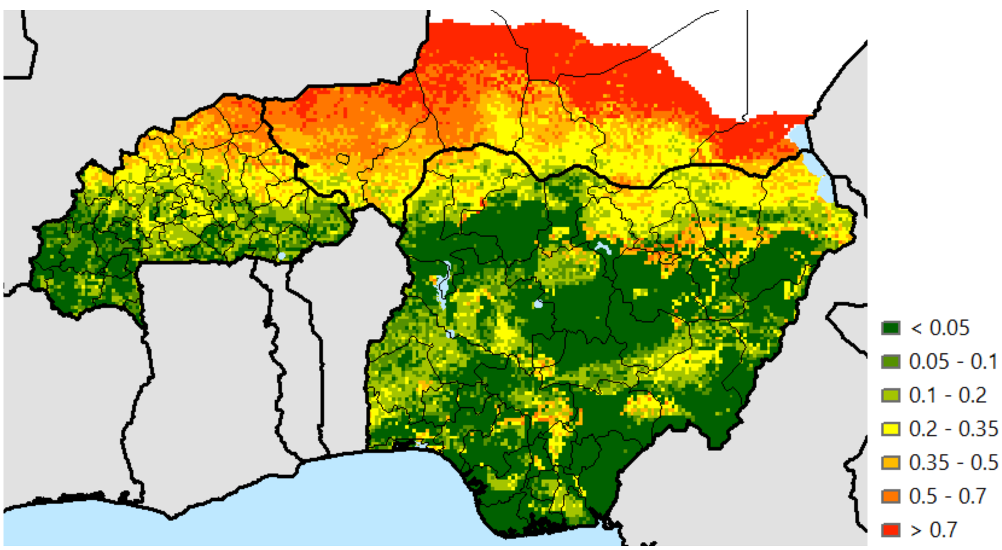
Source: SPAM (You et al. 2014).

Figure 4. Simulated baseline levels of aflatoxins in Nigeria, Niger, and Burkina Faso (proportion of years over 4 ppb) for rainfed groundnuts and rainfed maize, 1960-1990

Rainfed groundnuts

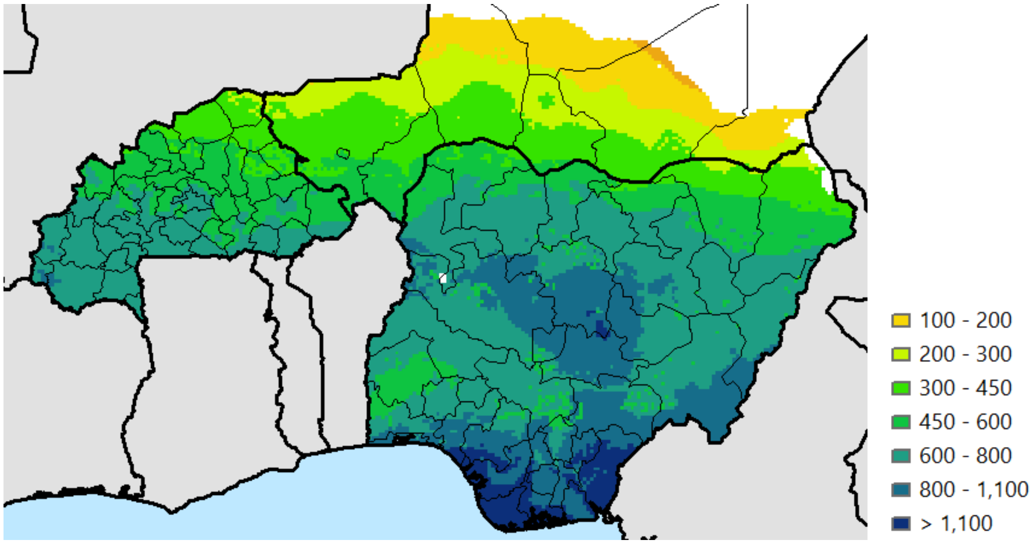


Rainfed maize



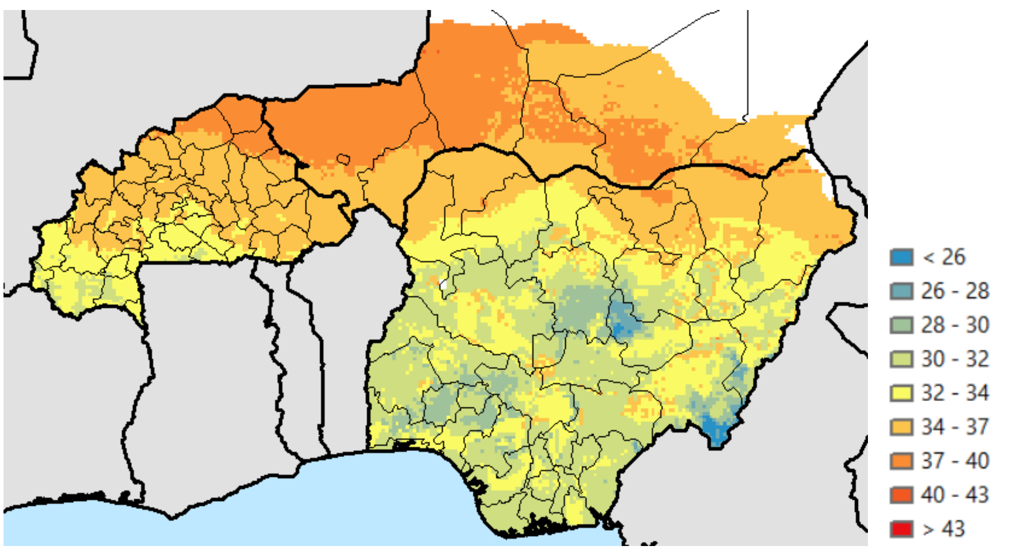
Source: Authors.

Figure 5. Rainfall levels in the first four months of the growing season for rainfed maize (each pixel has its optimal planting date)



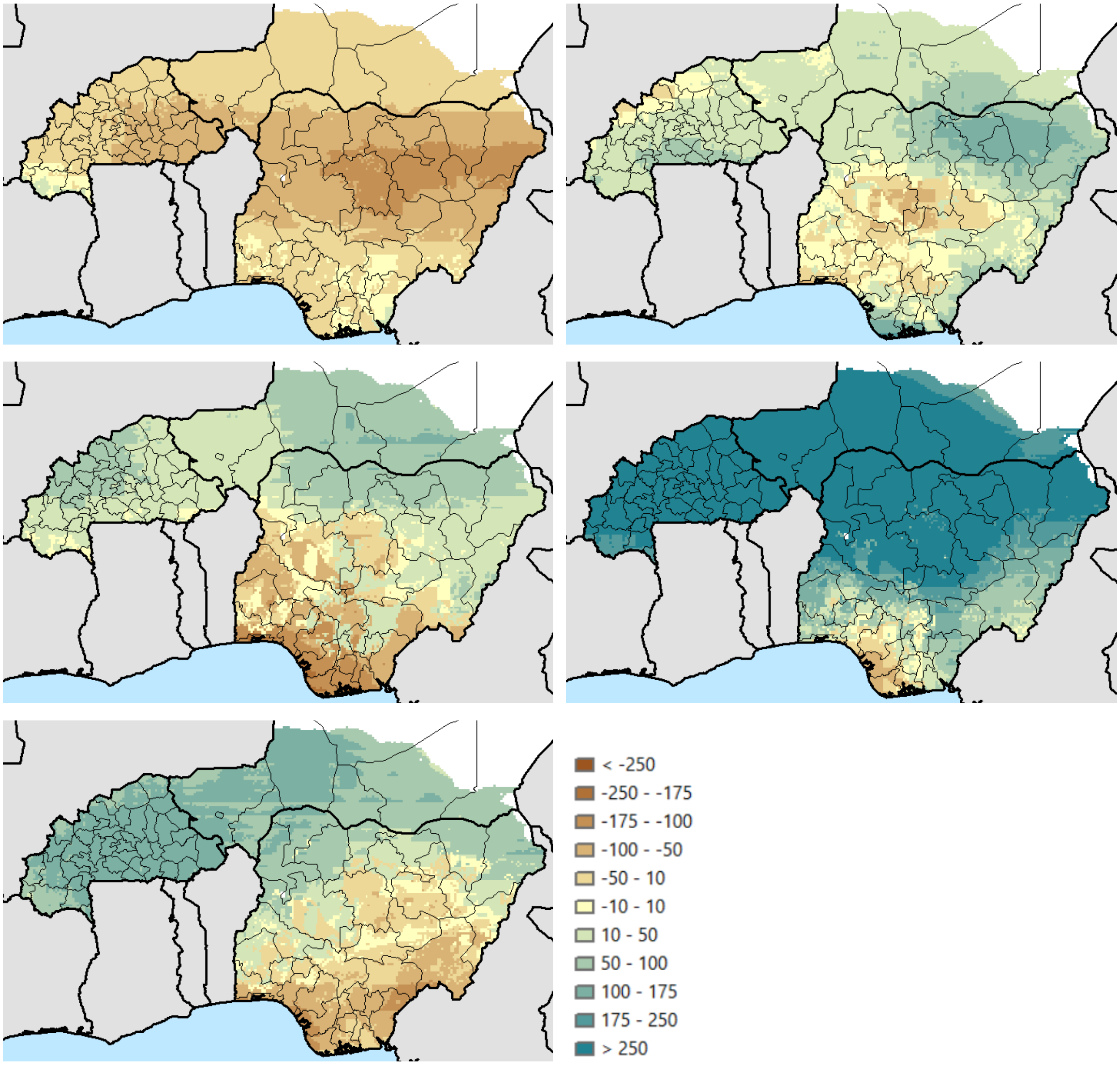
Source: Authors, based on WorldClim 1.4 (Hijmans et al. 2005)

Figure 6. Mean daily maximum temperature for the warmest month of the first four months of the growing season for rainfed maize.



Source: Authors, based on WorldClim 1.4 (Hijmans et al. 2005)

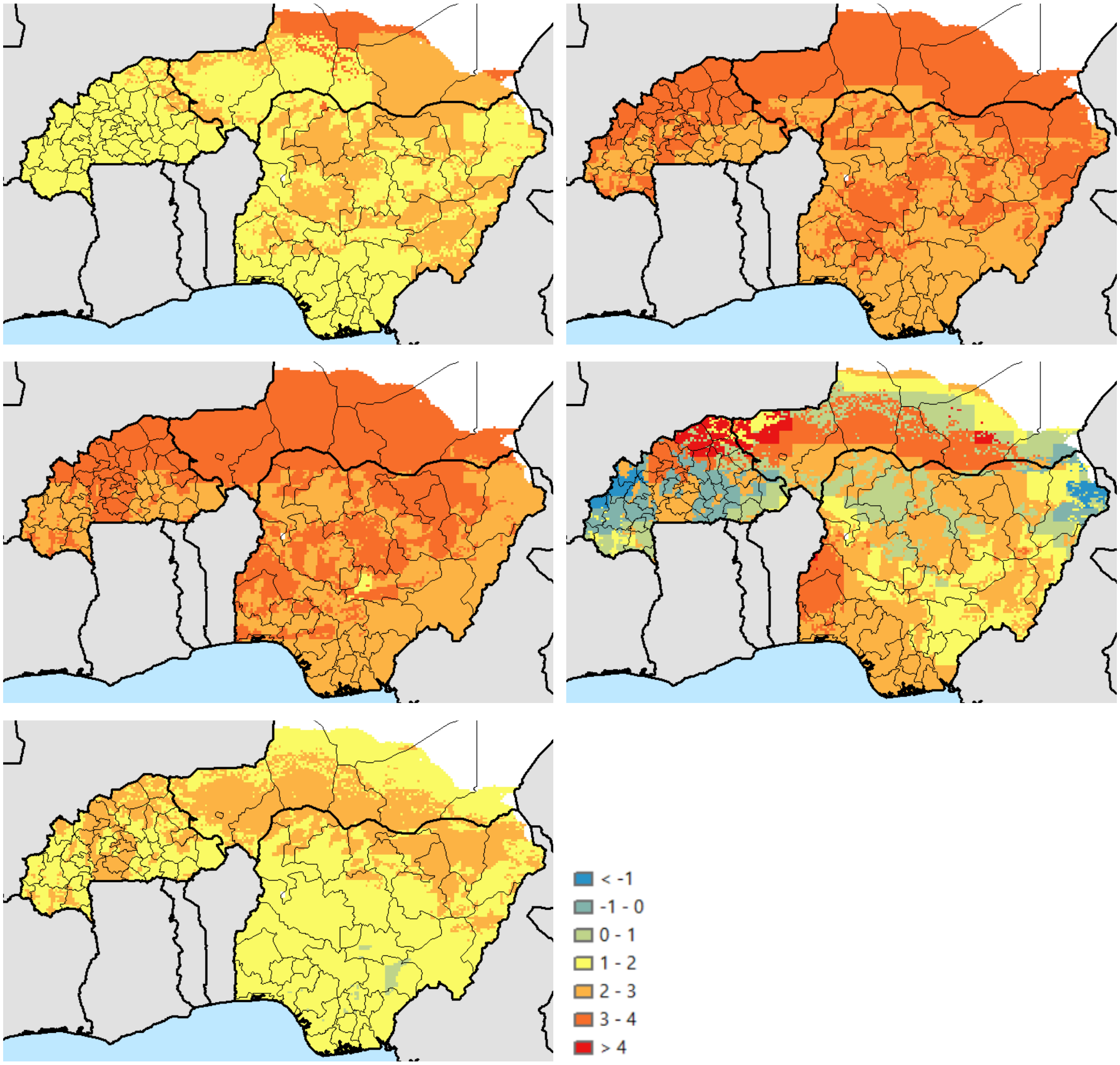
Figure 7. Change in rainfall levels in the first four months of the growing season for rainfed maize (each pixel has its optimal planting date) for GCM scenarios to 2050 compared to baseline



Source: Authors.

Notes: Top left –GFDL; top right – HadGEM; middle left – IPSL; middle right – MIROC; bottom left – NorES.

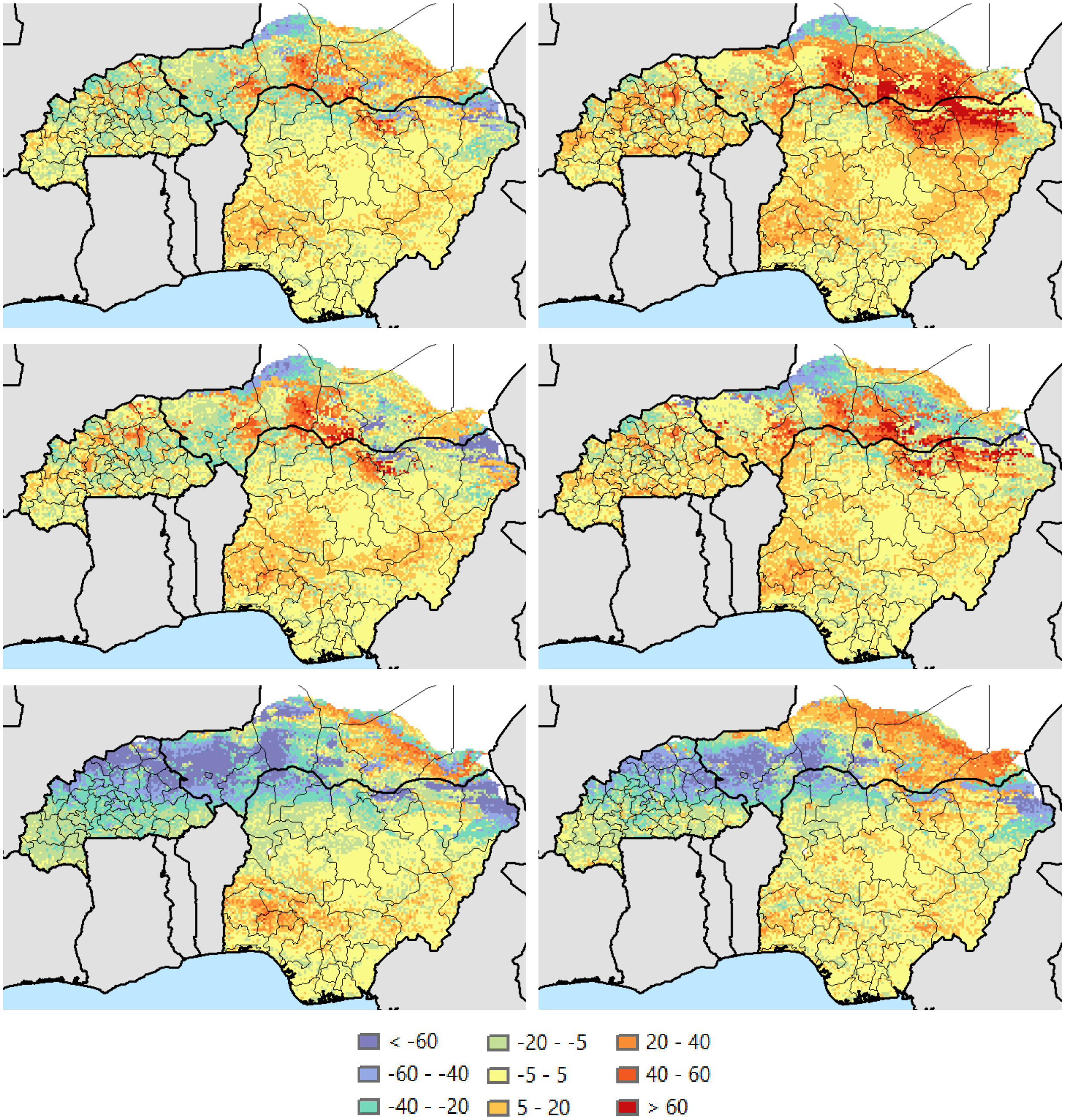
Figure 8. Change in mean daily maximum temperature for the warmest month of the first four months of the growing season for rainfed maize, for five GCM scenarios, baseline to 2050



Source: Authors.

Notes: Top left –GFDL; top right – HadGEM; middle left – IPSL; middle right – MIROC; bottom left – NorES.

Figure 9. Percentage point change in simulated baseline levels of aflatoxins in Nigeria, Niger, and Burkina Faso (proportion of years over 4 ppb) for rainfed groundnuts, from 1960-1990 to the 2050s, median values across 5 climate models used



Source: Authors.

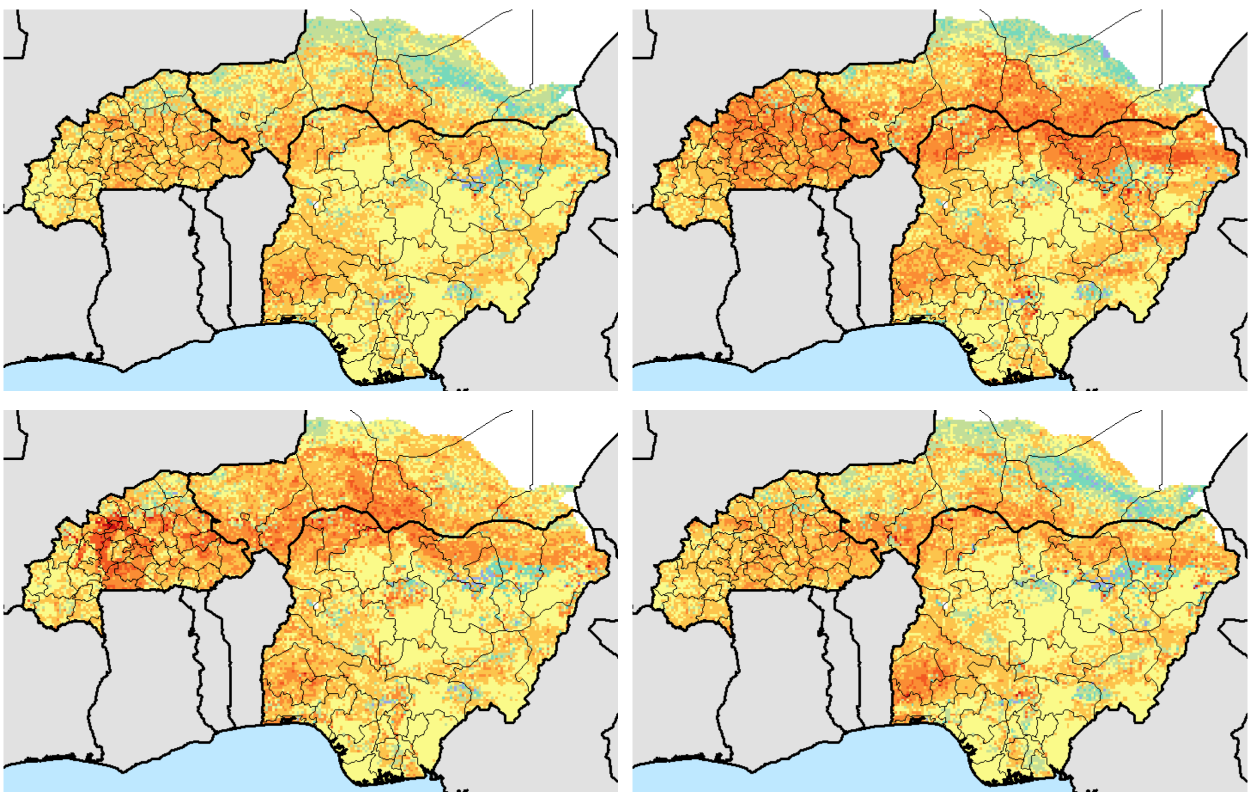
Notes: Top left, median across 5 climate models at each pixel; top right, GFDL; middle left, HadGEM; middle right, IPSL; bottom left, MIROC; bottom right, NorES.

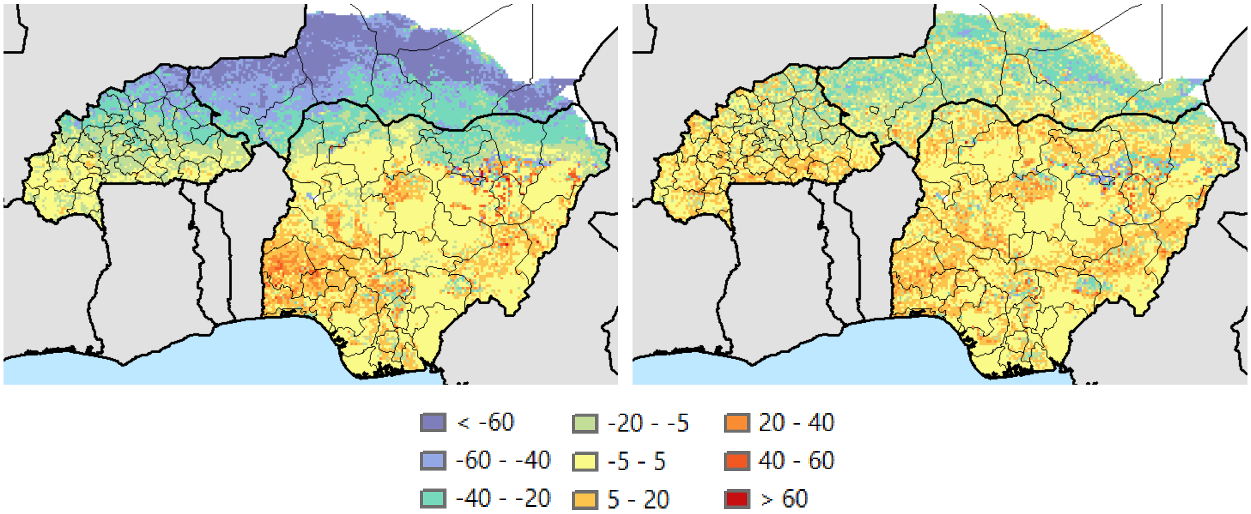
Table 1. Simulated groundnut aflatoxin levels by country (percent of pixels having greater than 4 ppb)

Country	Ground-nut hectares	Baseline, (1960-1990 climate)	Climate of 2050				
			GFDL	HadGEM	IPSL	MIROC	NorES
Burkina Faso	312,780	38.8%	42.7%	34.3%	42.5%	3.8%	11.6%
Niger	322,613	55.7%	85.4%	60.6%	74.4%	29.7%	41.9%
Nigeria	2,169,602	14.0%	25.0%	16.9%	18.5%	5.5%	11.0%

Source: Authors.

Figure 10. Percentage point change in simulated baseline levels of aflatoxins in Nigeria, Niger, and Burkina Faso (proportion of years over 4 ppb) for rainfed maize, from 1960-1990 to the 2050s, median values across 5 climate models, and the 5 climate models used





Source: Authors.

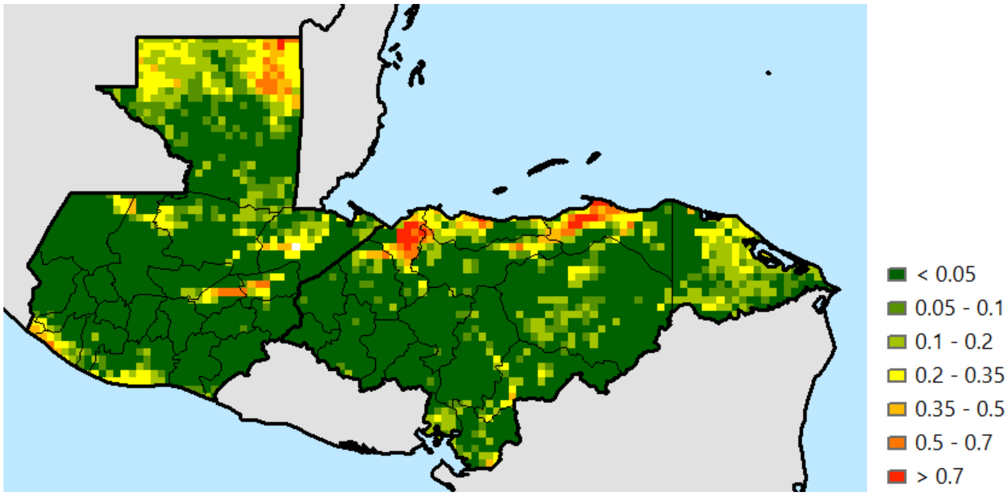
Notes: Top left, median across 5 climate models at each pixel; top right, GFDL; middle left, HadGEM; middle right, IPSL; bottom left, MIROC; bottom right, NorES.

Table 2. Simulated rainfed maize aflatoxin frequencies of exceeding 4 ppb by country (percent)

Country	Maize hectares	Baseline, (1960-1990 climate)	Climate of 2050				
			GFDL	HadGEM	IPSL	MIROC	NorES
Burkina Faso	419,938	7.6%	22.1%	18.5%	16.3%	2.3%	10.9%
Niger	7,496	42.8%	62.1%	54.1%	48.2%	1.5%	27.9%
Nigeria	3,623,435	8.9%	18.0%	15.3%	13.8%	11.5%	12.5%
Guatemala	687,515	4.4%	6.0%	27.6%	28.8%	15.9%	14.6%
Honduras	283,202	9.5%	11.4%	43.4%	46.1%	41.8%	33.2%
Nepal	268,459	0.2%	7.2%	1.0%	2.0%	0.8%	0.6%

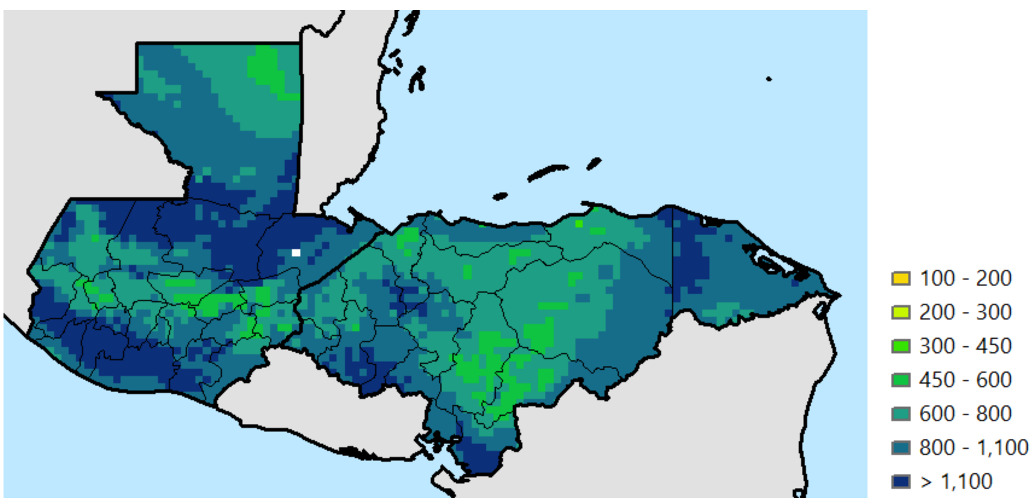
Source: Authors.

Figure 11. Simulated baseline levels of aflatoxins in Guatemala and Honduras (proportion of years over 4 ppb) for rainfed maize, 1960-1990



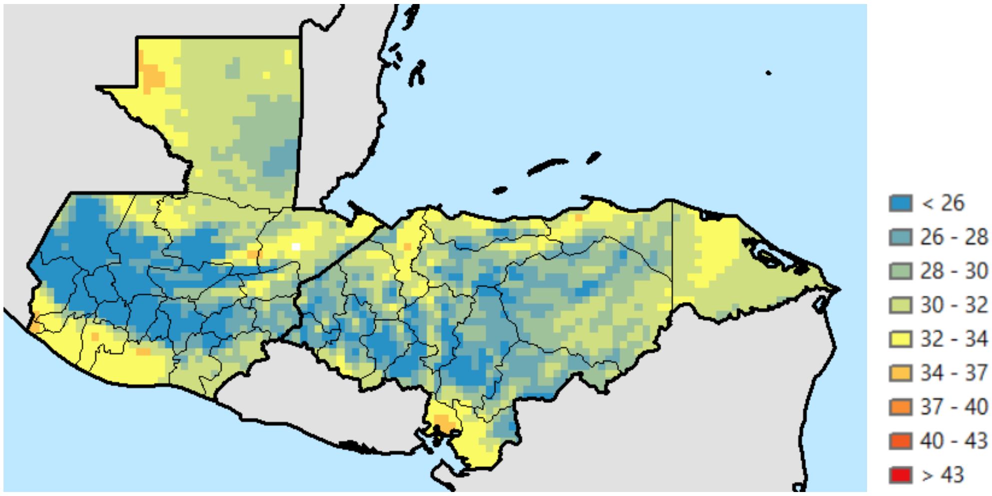
Source: Authors.

Figure 12. Rainfall levels in the first four months of the growing season for rainfed maize in Guatemala and Honduras (each pixel has its optimal planting date)



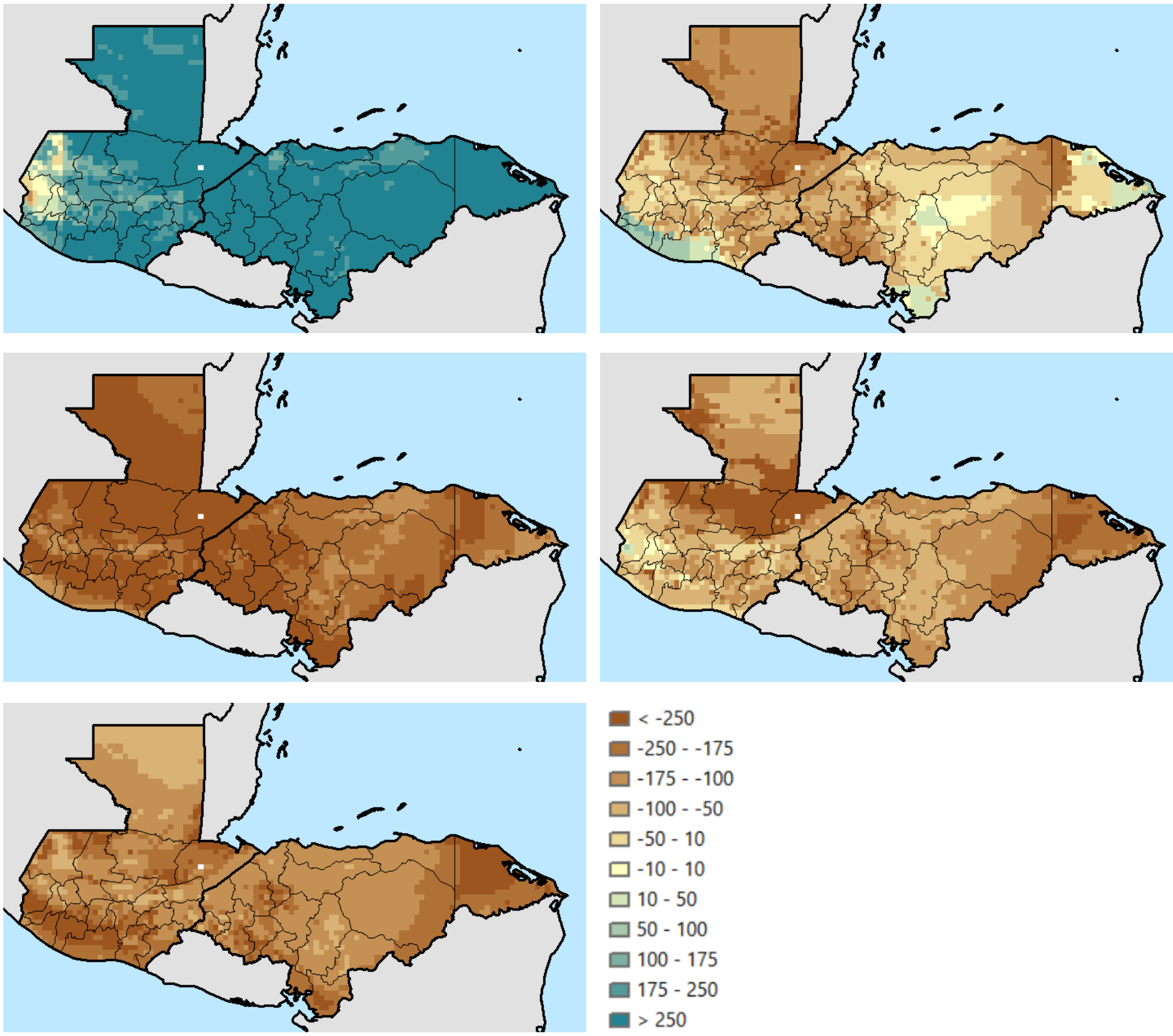
Source: Authors, based on WorldClim 1.4 (Hijmans et al. 2005)

Figure 13. Mean daily maximum temperature for the warmest month of the first four months of the growing season for rainfed maize in Guatemala and Honduras.



Notes: Top left – Mean daily maximum temperature for the warmest month among the first 4 months of the growing period for baseline years (in degrees C); the other five maps are for change in mean daily maximum temperature from baseline to 2050 for 5 different climate models (in millimeters). Top right – GFDL; mi ddle left – HadGEM; middle right – IPSL; bottom left – MIROC; bottom right – NorES.

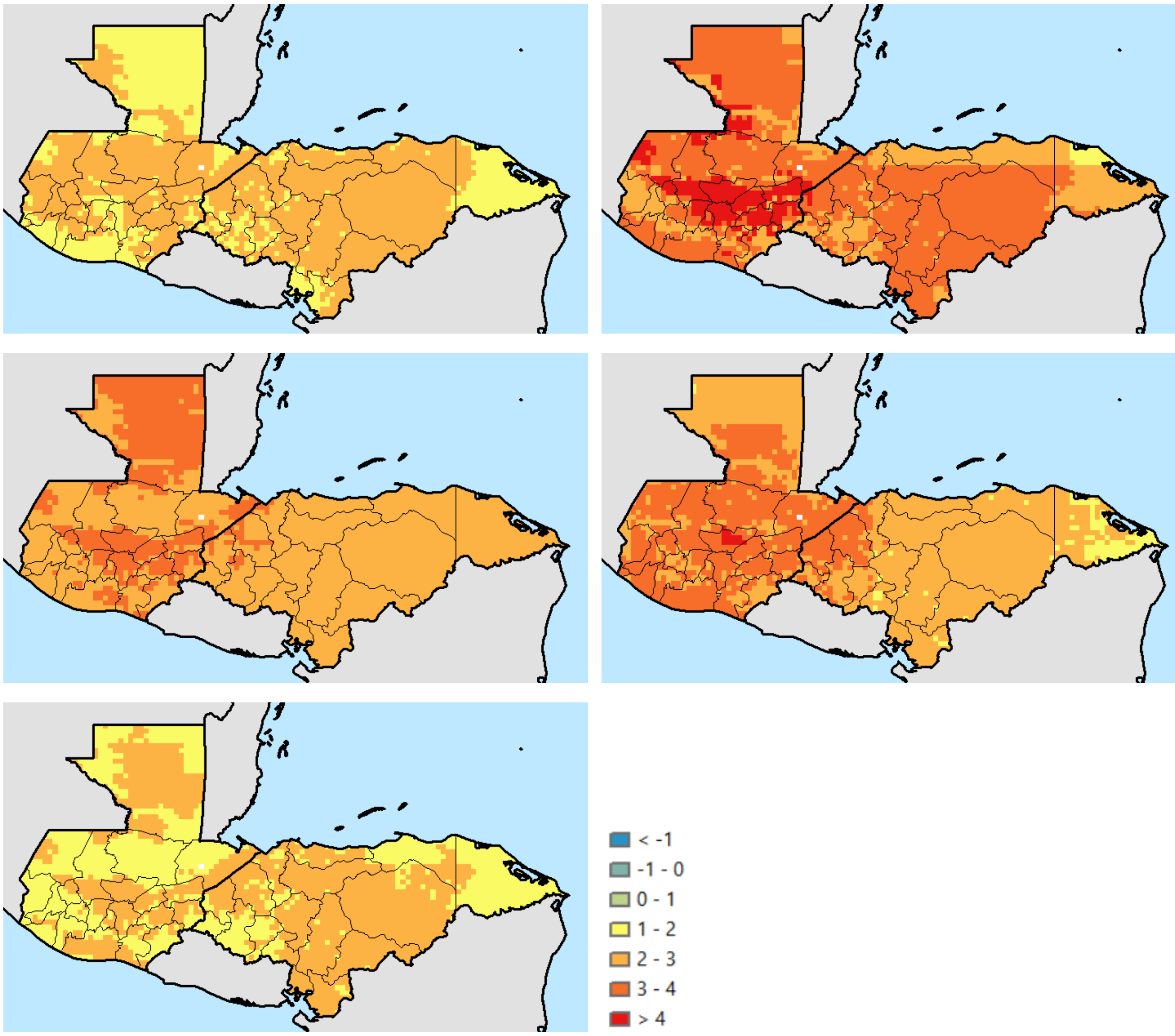
Figure 14. Change in rainfall levels in the first four months of the growing season for rainfed maize for Guatemala and Honduras, between the baseline and 2050



Source: Authors.

Notes: Top left –GFDL; top right – HadGEM; middle left – IPSL; middle right – MIROC; bottom left – NorES.

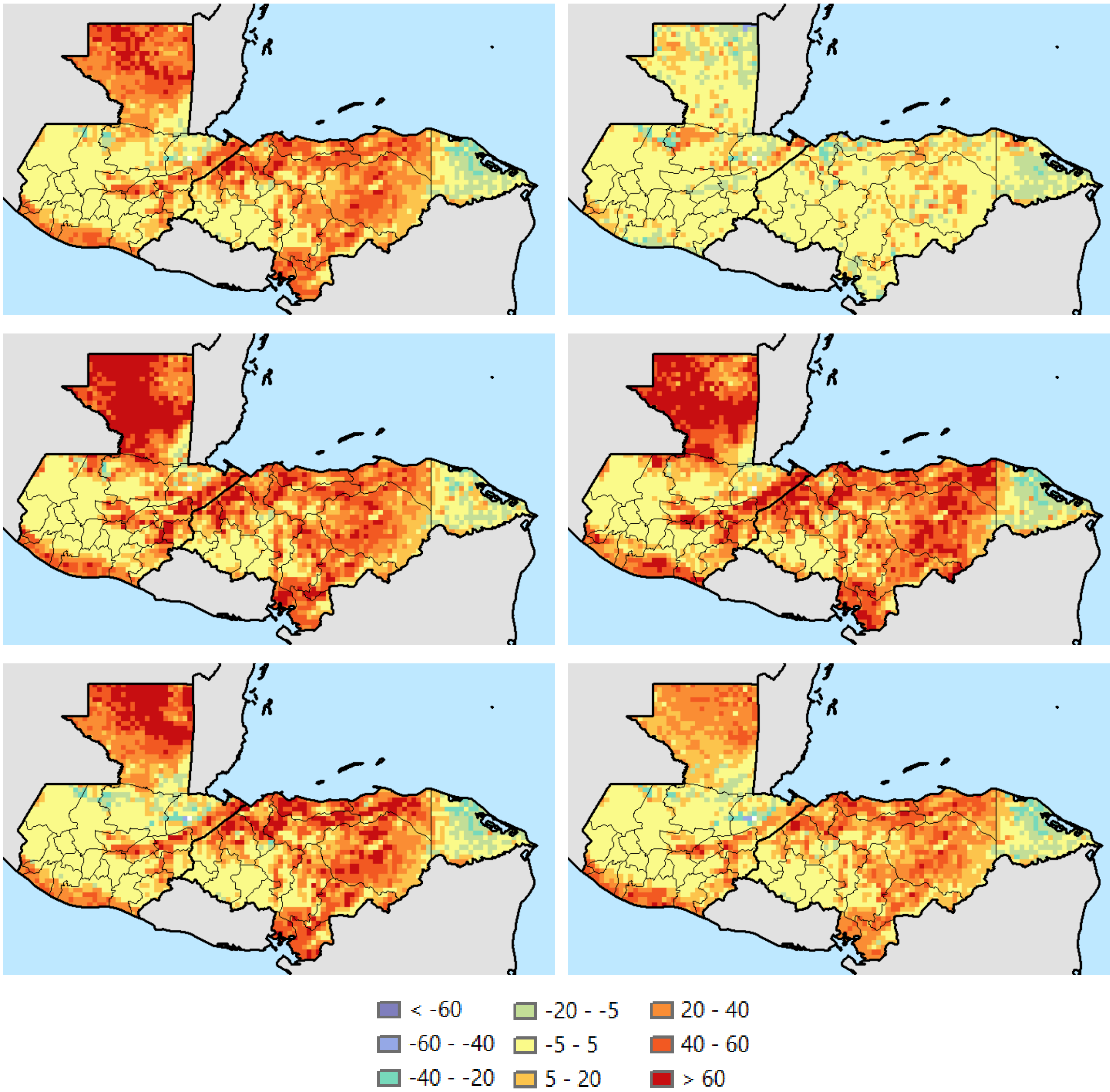
Figure 15. Change in mean daily maximum temperature for the warmest month of the first four months of the growing season for rainfed maize for Guatemala and Honduras, between the baseline and 2050



Source: Authors.

Notes: Top left –GFDL; top right – HadGEM; middle left – IPSL; middle right – MIROC; bottom left – NorES.

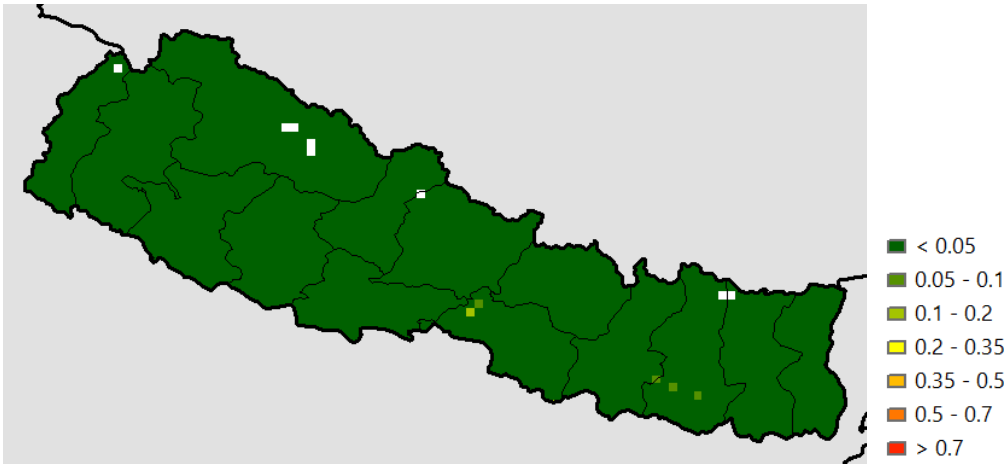
Figure 16. Percentage point change in simulated baseline levels of aflatoxins in Guatemala and Honduras (proportion of years over 4 ppb) for rainfed maize, from 1960-1990 to the 2050s, median values across 5 climate models, and the 5 climate models used



Source: Authors.

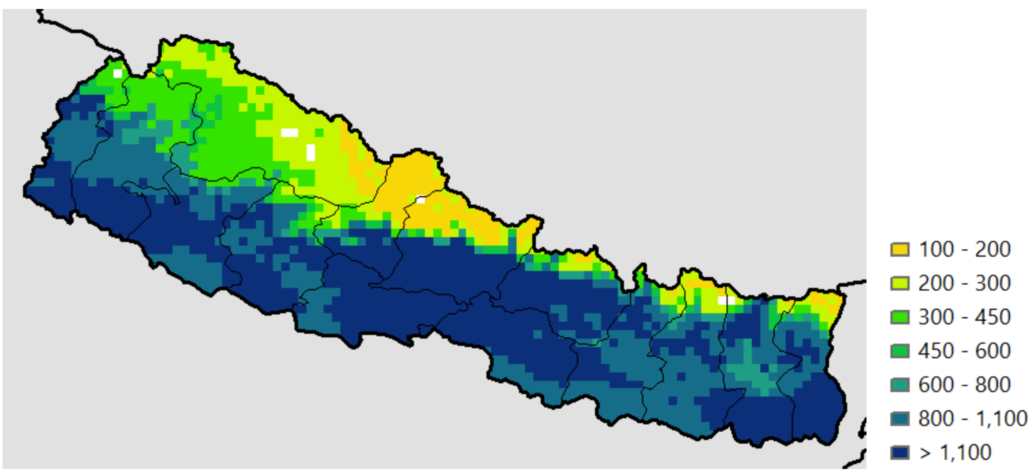
Notes: Top left, median across 5 climate models at each pixel; top right, GFDL; middle left, HadGEM; middle right, IPSL; bottom left, MIROC; bottom right, NorES.

Figure 17. Simulated baseline levels of aflatoxins in Nepal (proportion of years over 4 ppb) for rainfed maize, 1960-1990



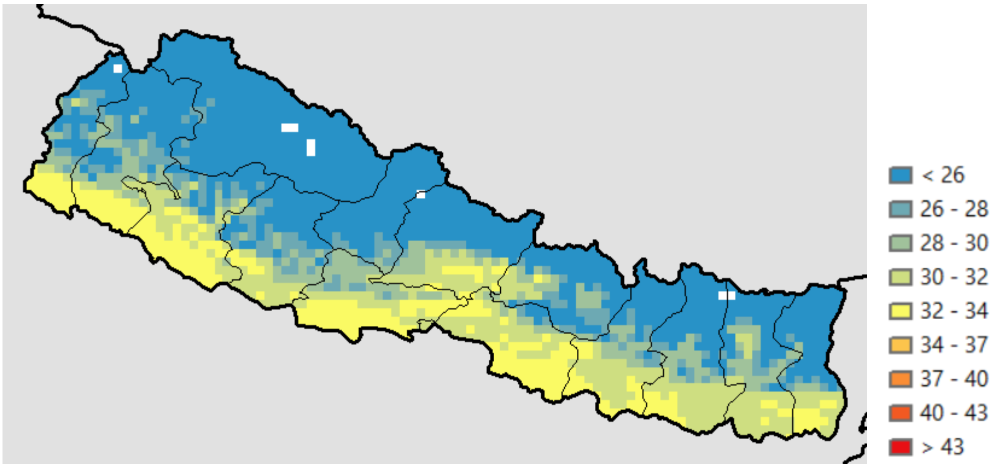
Source: Authors.

Figure 18. Rainfall levels in the first four months of the growing season for rainfed maize (each pixel has its optimal planting date)



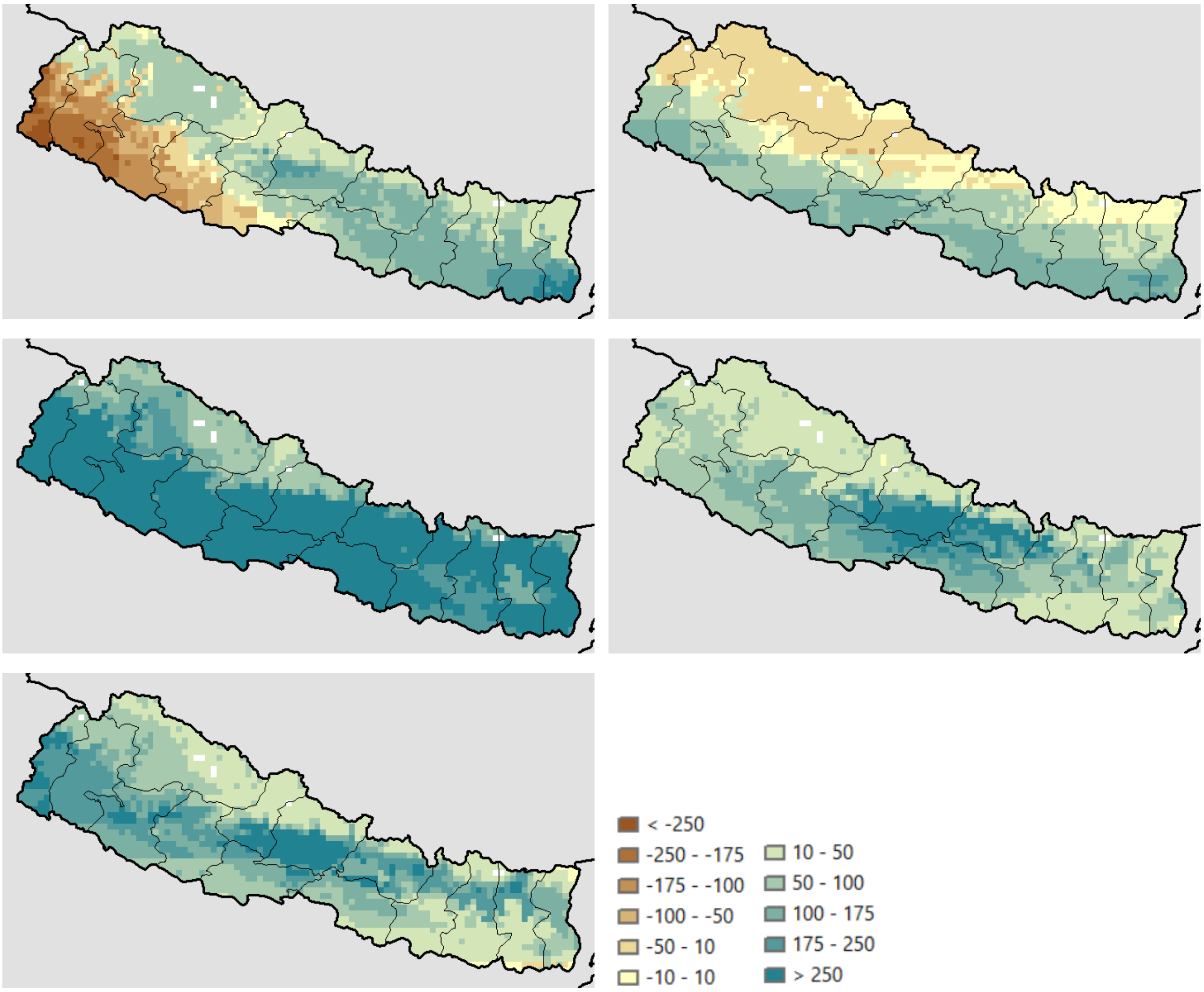
Source: Authors, based on WorldClim 1.4 (Hijmans et al. 2005)

Figure 19. Mean daily maximum temperature for the warmest month of the first four months of the growing season for rainfed maize.



Notes: Top left – Mean daily maximum temperature for the warmest month among the first 4 months of the growing period for baseline years (in degrees C); the other five maps are for change in mean daily maximum temperature from baseline to 2050 for 5 different climate models (in millimeters). Top right – GFDL; mi ddle left – HadGEM; middle right – IPSL; bottom left – MIROC; bottom right – NorES.

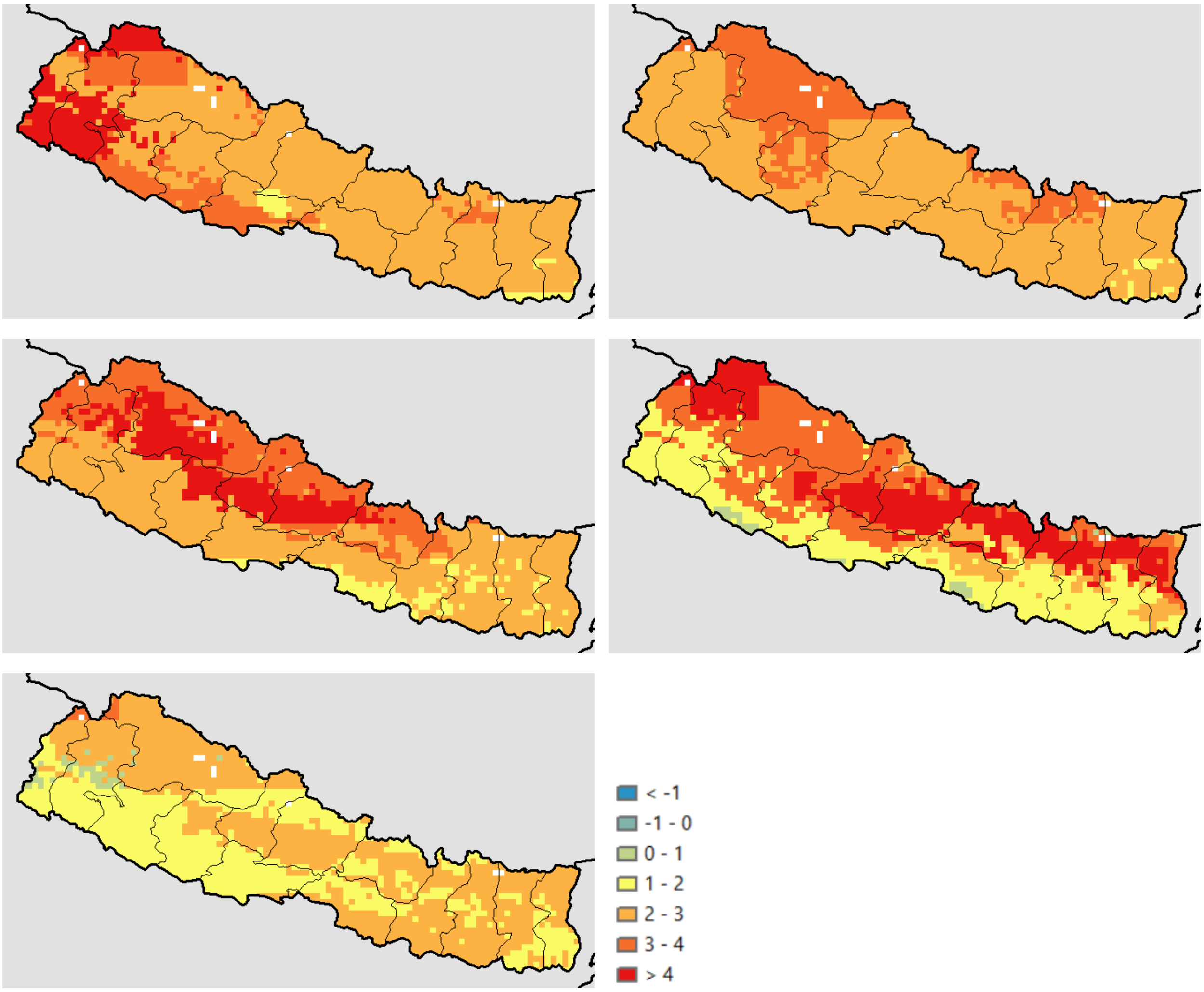
Figure 20. Change in rainfall levels in the first four months of the growing season for rainfed maize for Nepal, baseline to 2050



Source: Authors.

Notes: Top left –GFDL; top right – HadGEM; middle left – IPSL; middle right – MIROC; bottom left – NorES.

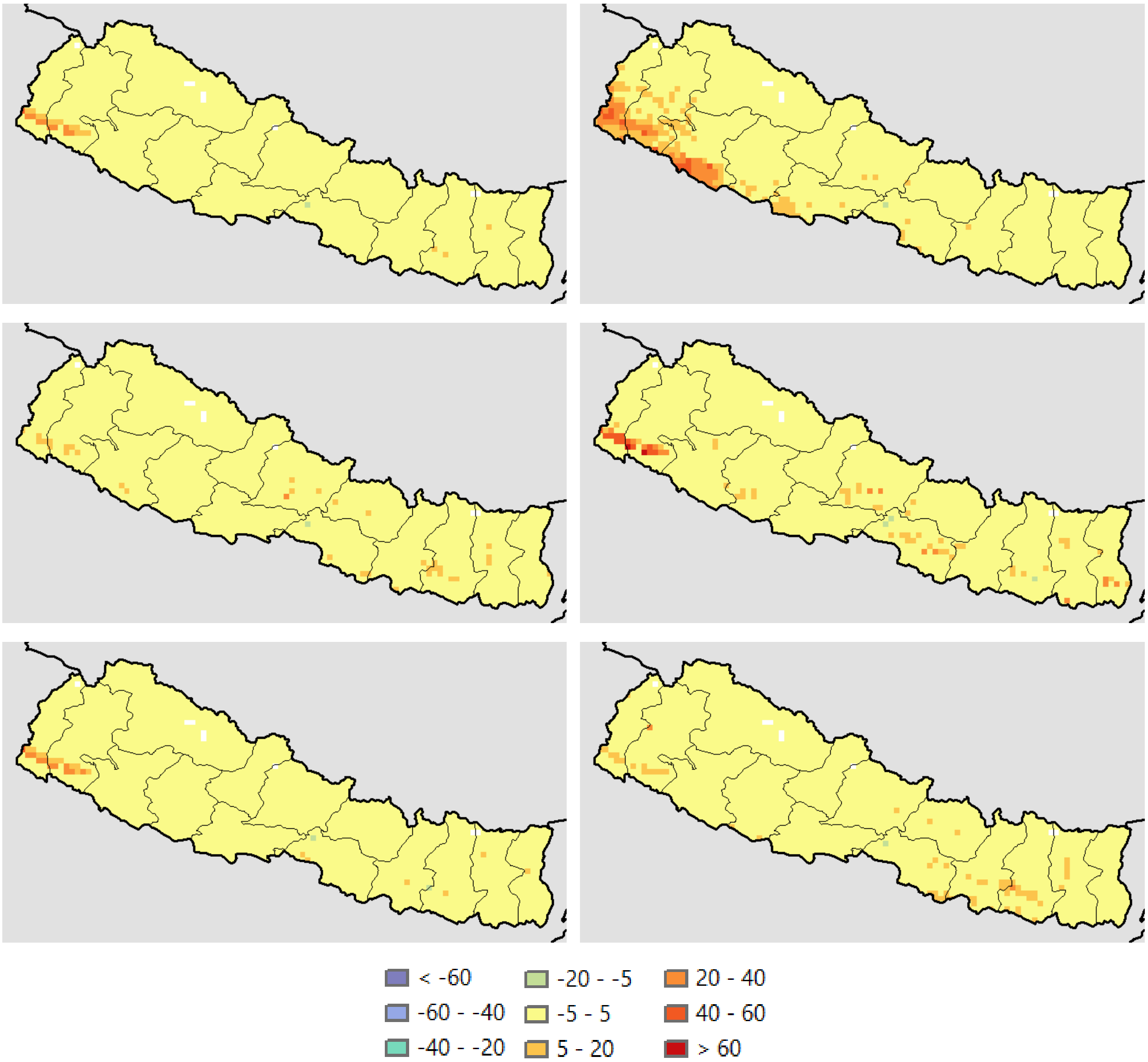
Figure 21. Change in mean daily maximum temperature for the warmest month of the first four months of the growing season for rainfed maize for Nepal, baseline to 2050



Source: Authors.

Notes: Top left –GFDL; top right – HadGEM; middle left – IPSL; middle right – MIROC; bottom left – NorES.

Figure 22. Percentage point change in simulated baseline levels of aflatoxins in Nepal (proportion of years over 4 ppb) for rainfed maize, from 1960-1990 to the 2050s, median values across 5 climate models, and the 5 climate models used



Source: Authors.

Notes: Top left, median across 5 climate models at each pixel; top right, GFDL; middle left, HadGEM; middle right, IPSL; bottom left, MIROC; bottom right, NorES.

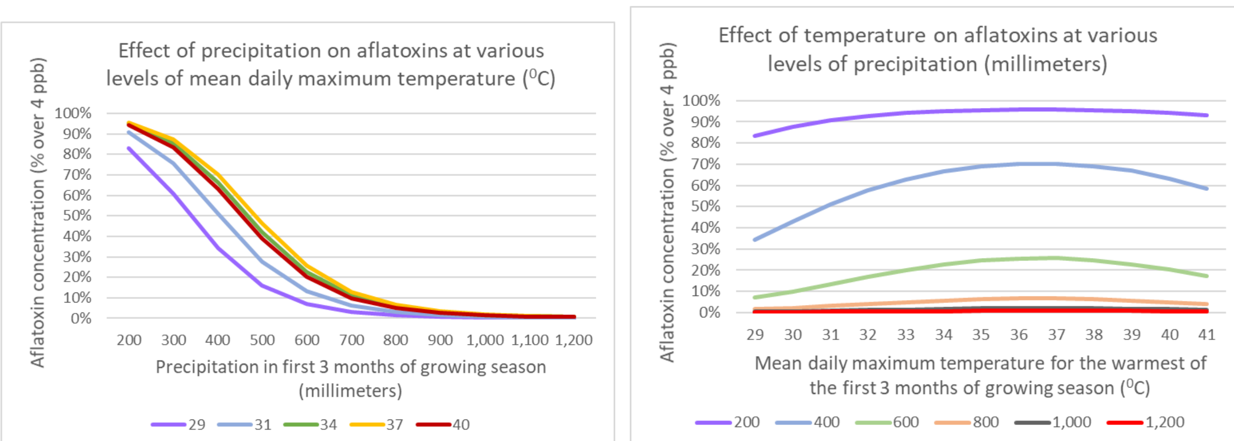
Table 3. Regression of weather variables on frequency of groundnut aflatoxin levels exceeding 4 ppb in the field, from DSSAT aflatoxin module

Parameter	Coef.	Std. Err.	t	P>t
Rain, growing season	-.0137598	.0000797	-172.55	0.000
- square	4.17e-06	4.74e-08	87.88	0.000
Mean daily max temp, warmest month of growing season	1.928767	.0229525	84.03	0.000
- square	-.0263749	.0003296	-80.02	0.000
Constant	-29.56882	.392665	-75.30	0.000

Source: Authors.

Notes: 145,020 observations, R-squared of 0.6668.

Figure 23. Effect of precipitation and mean daily maximum temperature in the growing season on groundnut aflatoxins



Source: Authors.

Notes: Based on output from the DSSAT aflatoxin module. Analysis was done for 6 different climates, and was limited to the area of Nigeria, Niger, and Burkina Faso.

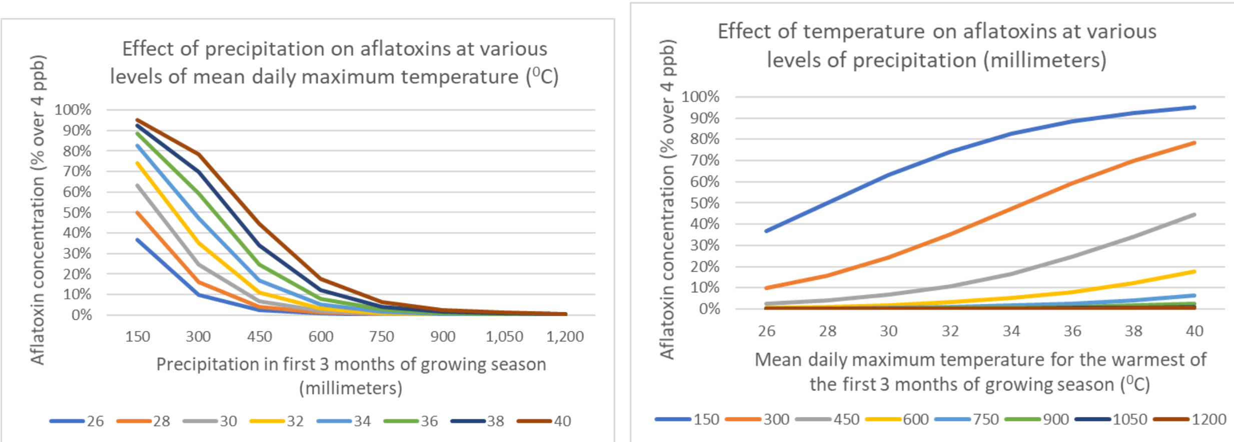
Table 4. Regression of weather variables on frequency of rainfed maize aflatoxin levels exceeding 4 ppb in the field, from DSSAT aflatoxin module

Parameter	Coef.	Std. Err.	t	P>t
Rain, growing season	-.0128527	.0000455	-282.71	0.000
- square	3.82e-06	2.65e-08	144.11	0.000
Mean daily max temp, warmest month of growing season	.3973385	.0118917	33.41	0.000
- square	-.0022296	.0001729	-12.89	0.000
Elevation	-.0019489	.0000152	-128.60	0.000
- square	1.99e-07	4.23e-09	47.17	0.000
Soil type 2	.5314947	.046788	11.36	0.000
Soil type 3	1.409604	.0371401	37.95	0.000
Soil type 4	-.1094114	.0309892	-3.53	0.000
Soil type 5	-.1740296	.0408123	-4.26	0.000
Soil type 10	-.811437	.0207797	-39.05	0.000
Soil type 11	.231663	.0297857	7.78	0.000
Soil type 12	-.2449777	.0222682	-11.00	0.000
Soil type 13	-1.275002	.0168521	-75.66	0.000
Soil type 14	-1.51527	.0366227	-41.38	0.000
Soil type 15	-.5108699	.0185765	-27.50	0.000
Soil type 16	-.9503066	.0229588	-41.39	0.000
Soil type 17	.9854337	.1648294	5.98	0.000
Soil type 18	-.6100542	.0572479	-10.66	0.000
Soil type 19	-.6604056	.0688694	-9.59	0.000
Soil type 21	-.2902645	.0624854	-4.65	0.000
Soil type 22	-.4846947	.0506076	-9.58	0.000
Soil type 23	-.7498506	.0697524	-10.75	0.000
Soil type 25	-1.055636	.0205739	-51.31	0.000
Soil type 26	-1.973082	.0203166	-97.12	0.000
Soil type 27	-.8877667	.0218381	-40.65	0.000
Constant	-5.689427	.2101198	-27.08	0.000

Source: Authors.

Notes: 202,584 observations, R-squared of 0.7484.

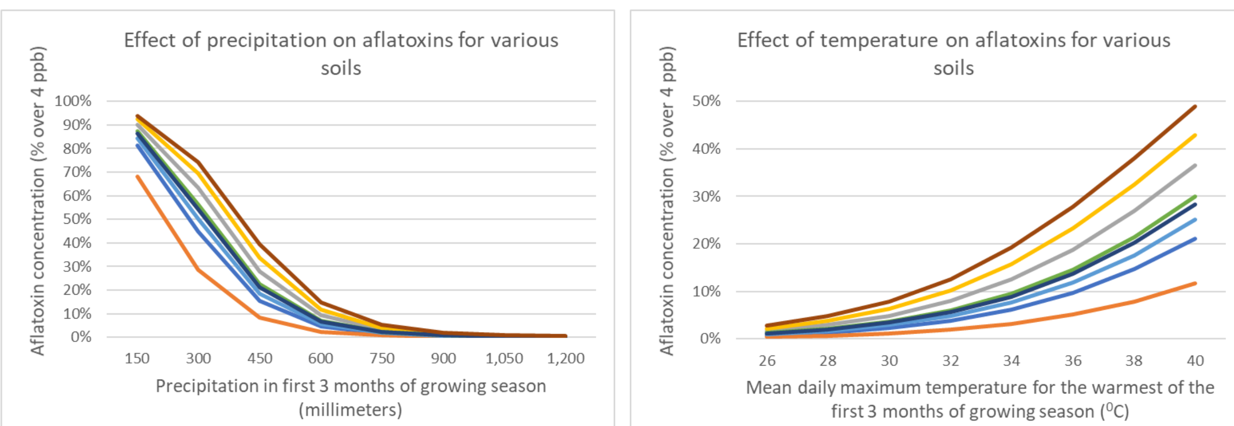
Figure 24. Effect of precipitation and mean daily maximum temperature in the growing season on rainfed maize aflatoxins



Source: Authors.

Notes: Based on output from the DSSAT aflatoxin module. Analysis was done for 6 different climates, and was limited to the area of Nepal, Guatemala, Honduras, Nigeria, Niger, and Burkina Faso. Graphs are based on median elevation and the most widely observed soil type in the sample.

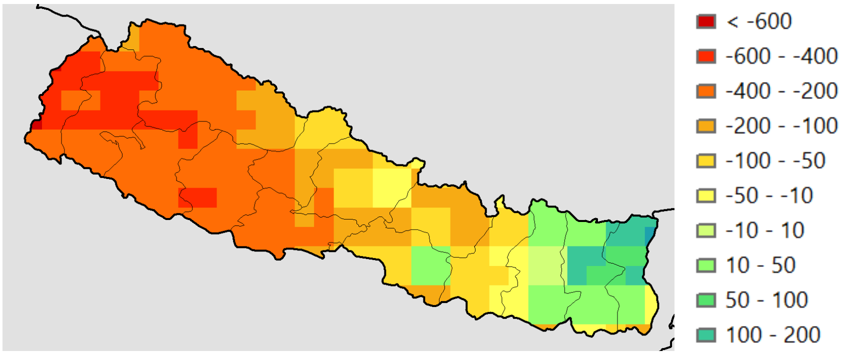
Figure 25. Effect of precipitation and temperature in the growing season on rainfed maize aflatoxins for different soil types



Source: Authors.

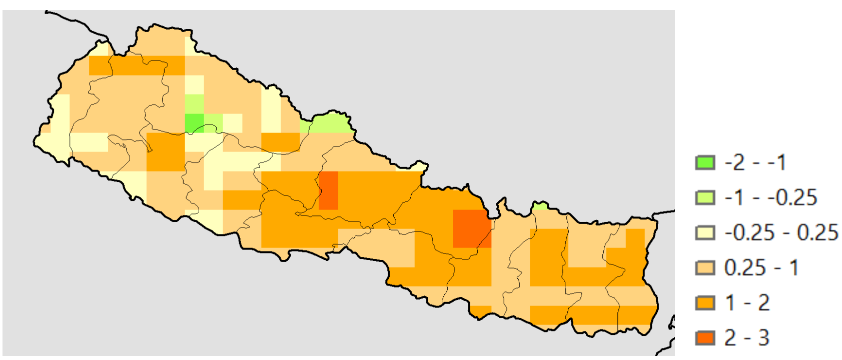
Notes: Based on output from the DSSAT aflatoxin module. Analysis was done for 6 different climates, and was limited to the area of Nepal, Guatemala, Honduras, Nigeria, Niger, and Burkina Faso. Graphs are based on median elevation, and as appropriate, median precipitation and temperature.

Figure 26. Trend in annual rainfall in Nepal between 1980 to 2010, millimeters



Source: Authors, using AgMERRA data (Ruane at al. 2013).

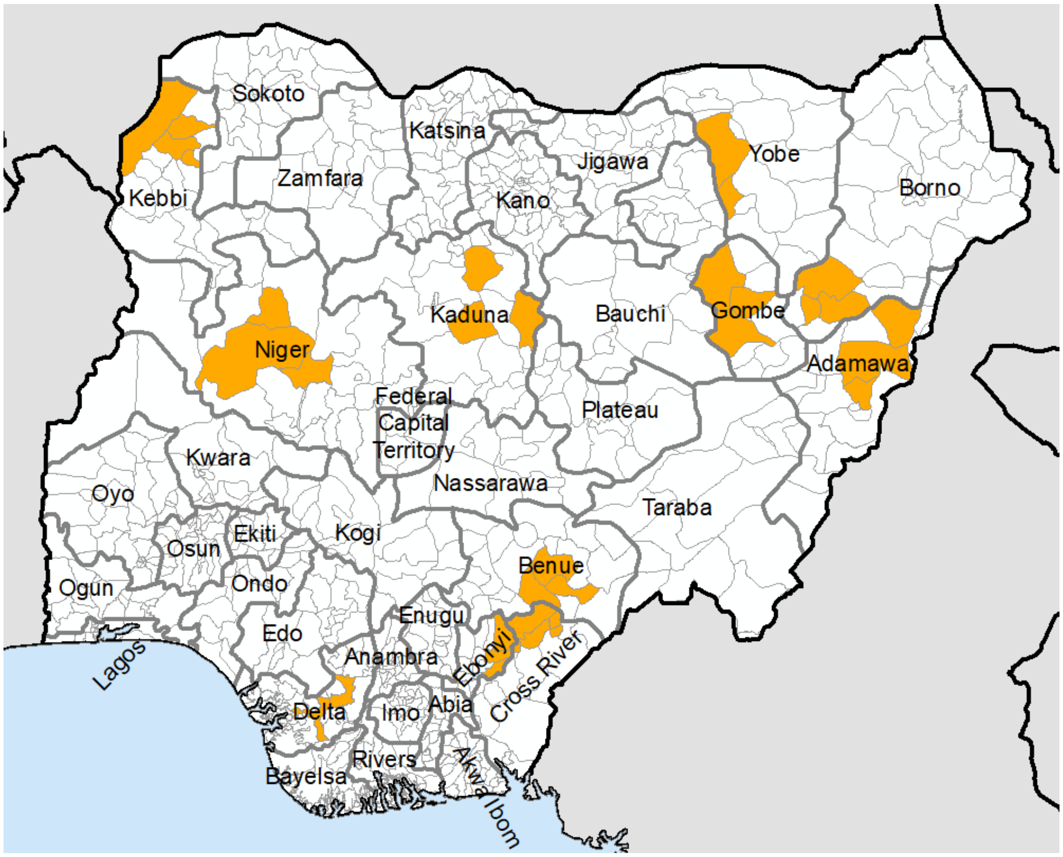
Figure 27. Trend in mean daily maximum temperature of the warmest month in Nepal between 1980 to 2010, ^{0}C



Source: Authors, using AgMERRA data (Ruane at al. 2013).

Appendix

Appendix Figure 1. Nigeria states, local government areas (LGAs), and Feed the Future (FTF) Zones of Influence (ZoIs)



Source: Natural Earth provides boundaries for nations and states; LGAs and ZoIs are from GADM 2.1.

Notes: ZoIs are in orange.

Appendix Table 1. Simulated groundnut aflatoxin contamination in Nigeria by state (percent of time that levels exceed 4 ppb)

State	Ground-nut hectares	Baseline, (1960-1990 climate)	Climate of 2050				
			GFDL	HadGEM	IPSL	MIROC	NorES
Abia	446	3.6%	5.3%	2.1%	1.8%	1.7%	4.3%
Adamawa	50,745	9.7%	18.6%	13.4%	14.4%	9.9%	8.0%
Akwa Ibom	54	8.7%	9.5%	0.3%	3.0%	0.0%	5.4%
Anambra	92	7.7%	11.2%	9.4%	5.5%	4.0%	5.5%
Bauchi	146,396	6.0%	25.2%	5.6%	10.8%	1.9%	8.5%
Bayelsa	36	3.0%	2.0%	1.1%	1.4%	0.9%	1.9%
Benue	193,611	4.8%	6.7%	4.2%	3.8%	7.2%	6.8%
Borno	103,372	37.4%	47.4%	25.4%	39.6%	7.0%	15.8%
Cross River	9,438	4.2%	3.9%	3.4%	2.2%	1.7%	3.5%
Delta	862	3.6%	4.4%	2.1%	2.2%	1.4%	3.0%
Ebonyi	8,877	2.0%	1.8%	2.1%	1.4%	1.7%	3.9%
Edo	3,448	6.9%	8.1%	7.8%	7.1%	8.8%	7.3%
Ekiti	58	2.0%	12.0%	16.0%	16.0%	8.0%	6.0%
Enugu	2,246	3.9%	3.5%	5.2%	4.9%	5.1%	6.2%
Fed Cap Terr	2,318	5.7%	9.4%	8.4%	6.4%	4.9%	5.2%
Gombe	34,763	7.5%	19.4%	8.7%	10.1%	5.2%	7.4%
Imo	126	2.7%	3.0%	1.6%	0.6%	1.8%	3.8%
Jigawa	75,631	34.0%	72.2%	39.4%	52.8%	12.3%	31.2%
Kaduna	206,479	3.5%	6.2%	4.8%	4.7%	0.7%	4.8%
Kano	397,398	16.7%	36.8%	28.8%	26.5%	2.6%	15.0%
Katsina	104,666	19.0%	33.1%	21.9%	22.0%	5.1%	12.8%
Kebbi	36,419	18.1%	22.2%	15.0%	24.0%	2.2%	7.3%
Kogi	21,546	7.5%	10.8%	10.2%	7.7%	13.9%	8.2%
Kwara	9,265	11.4%	21.3%	19.4%	17.3%	18.4%	13.3%
Lagos	1,414	4.9%	5.8%	3.2%	6.2%	6.3%	8.4%
Nassarawa	66,193	4.8%	9.1%	9.4%	6.4%	5.1%	7.3%
Niger	227,986	7.9%	14.0%	11.9%	11.1%	5.9%	9.4%
Ogun	404	8.4%	10.8%	11.5%	7.4%	10.1%	13.5%
Ondo	668	5.2%	4.2%	6.5%	4.8%	8.2%	4.5%
Osun	134	7.2%	12.0%	15.2%	28.9%	21.2%	8.3%
Oyo	12,744	18.8%	33.4%	30.2%	33.2%	28.3%	24.1%
Plateau	48,377	6.6%	13.5%	11.0%	9.3%	4.9%	8.2%
Rivers	412	3.1%	4.0%	2.0%	1.7%	1.7%	3.0%
Sokoto	66,428	42.2%	46.3%	43.1%	46.0%	3.5%	10.7%
Taraba	148,875	13.6%	22.6%	20.0%	17.8%	16.0%	13.6%
Yobe	58,409	20.4%	54.0%	12.5%	34.5%	9.7%	19.8%
Zamfara	129,560	17.0%	15.3%	13.5%	15.2%	0.8%	3.9%

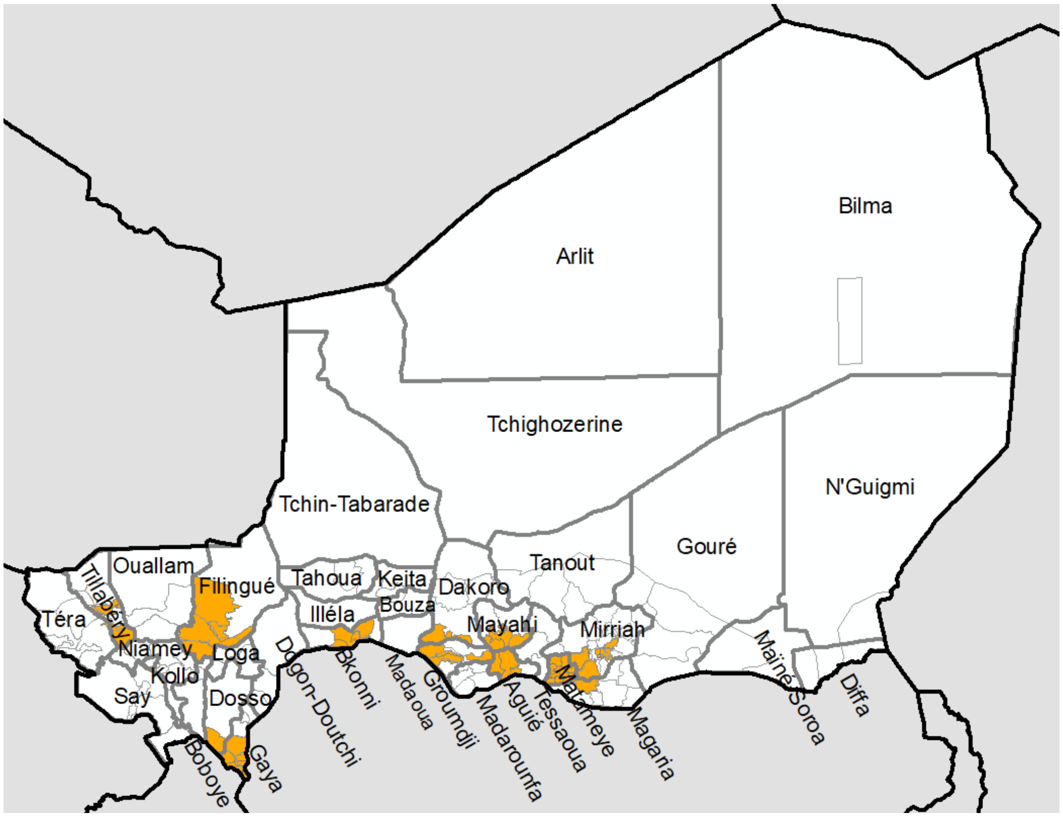
Source: Authors.

Appendix Table 2. Simulated groundnut aflatoxin contamination in Nigeria by Feed the Future Zones of Influence (percent of time that levels exceed 4 ppb)

				Climate of 2050				
State	LGA	Ground-nut hectares	Baseline	GFDL	HadGEM	IPSL	MIROC	NorES
Adamawa	Gombi	1,581	15.9%	25.9%	19.5%	22.5%	14.9%	13.6%
Adamawa	Hong	4,976	3.9%	12.1%	5.5%	6.5%	2.8%	4.5%
Adamawa	Song	3,819	11.0%	15.5%	16.3%	15.3%	8.5%	6.7%
Benue	Gboko	12,159	1.9%	5.0%	1.6%	1.0%	6.0%	7.7%
Benue	Konshish	8,033	1.6%	7.5%	0.9%	1.2%	4.8%	2.8%
Benue	Ushongo	8,824	2.0%	9.3%	1.6%	2.3%	6.8%	3.7%
Borno	Biu	4,210	9.1%	17.1%	6.9%	12.9%	1.4%	3.7%
Borno	Hawul	2,981	7.6%	11.3%	6.7%	10.7%	2.7%	3.7%
Borno	Kwaya Kusar	2,026	6.9%	10.2%	9.1%	14.9%	3.5%	4.9%
Cross River	Bekwarra	213	7.5%	8.5%	12.0%	5.5%	2.0%	7.0%
Cross River	Ogoja	512	4.9%	3.6%	5.1%	6.7%	1.2%	7.5%
Cross River	Yala Cross	3,866	6.0%	5.7%	4.8%	1.9%	2.6%	4.2%
Delta	Ndokwa West	68	4.2%	6.3%	1.8%	1.6%	1.8%	2.4%
Delta	Ughelli North	41	2.5%	5.6%	2.6%	0.3%	0.7%	2.5%
Ebonyi	Abakalik	664	1.5%	0.9%	3.5%	1.1%	0.4%	2.0%
Ebonyi	Ikwo	716	1.2%	0.8%	3.6%	0.8%	1.2%	3.6%
Ebonyi	Izzi	1,295	2.3%	1.9%	3.1%	1.3%	1.8%	3.8%
Gombe	Akko	6,208	6.9%	14.9%	10.0%	9.0%	5.2%	7.2%
Gombe	Dukku	6,746	2.6%	19.1%	1.6%	4.6%	0.7%	6.3%
Gombe	Kwami	2,543	7.3%	18.4%	5.8%	9.8%	3.5%	7.4%
Kaduna	Kajuru	6,250	0.8%	3.7%	1.2%	1.4%	0.0%	1.8%
Kaduna	Lere	15,782	1.1%	2.7%	2.0%	2.9%	0.0%	4.5%
Kaduna	Soba	13,373	6.4%	10.2%	7.4%	7.8%	1.6%	7.9%
Kebbi	Aleiro	628	22.5%	34.6%	25.6%	28.1%	10.7%	15.0%
Kebbi	Arewa	3,906	40.6%	43.2%	34.8%	53.4%	4.0%	11.8%
Kebbi	Argungu	1,476	27.5%	26.8%	25.0%	36.7%	0.9%	8.1%
Kebbi	BirninKe	1,428	21.1%	33.8%	19.1%	30.5%	2.7%	14.4%
Niger	Kontogur	6,993	5.7%	13.0%	8.1%	10.9%	2.3%	14.3%
Niger	Mashegu	17,215	6.9%	12.4%	11.2%	9.4%	5.3%	11.0%
Niger	Wushishi	4,253	8.2%	17.5%	18.1%	12.7%	8.2%	11.4%
Yobe	Jakusko	5,973	21.7%	77.5%	17.8%	57.0%	14.6%	28.2%
Yobe	Nangere	4,589	0.7%	25.4%	1.4%	2.7%	1.7%	6.5%

Source: Authors.

Appendix Figure 2. Niger departments, communes, and FTF ZoIs



Source: Natural Earth provides boundaries for nations and states; communes are from GADM 2.1.

Notes: ZoIs are in orange.

Appendix Table 3. Simulated groundnut aflatoxin contamination in Niger by region and department (percent of time that levels exceed 4 ppb)

				Climate of 2050				
Region	Department	Ground-nut hectares	Baseline	GFDL	HadGEM	IPSL	MIROC	NorES
Diffa	Diffa	1,581	96.5%	97.6%	37.2%	46.5%	56.3%	72.5%
Diffa	Mainé-Soroa	580	80.6%	98.2%	50.1%	30.0%	47.5%	72.5%
Dosso	Boboye	6,572	62.4%	60.7%	47.2%	70.9%	7.7%	15.0%
Dosso	Dogon-Doutchi	12,192	56.7%	80.7%	72.6%	81.5%	14.5%	27.7%
Dosso	Dosso	12,795	53.0%	65.1%	47.2%	69.4%	9.1%	20.1%
Dosso	Gaya	6,027	37.8%	48.9%	26.5%	49.3%	6.8%	14.6%
Dosso	Loga	5,346	63.7%	80.4%	73.2%	86.1%	13.0%	26.2%
Maradi	Aguie	13,675	23.1%	78.2%	62.8%	75.7%	11.1%	31.2%
Maradi	Dakoro	38,505	72.1%	93.0%	86.0%	87.4%	37.2%	44.8%
Maradi	Groumdji	22,359	49.5%	76.6%	82.5%	74.2%	10.1%	27.7%
Maradi	Madarounfa	15,336	34.3%	57.0%	68.1%	57.9%	6.2%	22.1%
Maradi	Mayahi	32,690	56.4%	95.3%	65.5%	88.7%	36.3%	45.0%
Maradi	Tessaoua	21,759	43.2%	90.3%	42.6%	88.9%	33.1%	46.6%
Niamey	Niamey	923	84.0%	77.7%	57.2%	72.6%	13.7%	20.8%
Tahoua	Bkonni	4,911	72.6%	85.6%	79.0%	76.4%	11.3%	20.8%
Tahoua	Bouza	5,431	53.5%	90.4%	92.3%	80.9%	30.1%	29.3%
Tahoua	Illela	4,471	81.6%	93.3%	86.9%	81.2%	15.7%	22.9%
Tahoua	Keita	3,060	55.2%	96.0%	91.5%	83.1%	32.0%	39.4%
Tahoua	Madaoua	6,584	45.8%	80.5%	80.7%	73.5%	10.5%	16.3%
Tahoua	Tahoua	4,748	86.7%	94.4%	91.8%	86.1%	24.3%	33.7%
Tahoua	Tchin-Tabarade	1,348	73.9%	96.9%	79.6%	61.6%	37.7%	56.1%
Tillabery	Filingue	1,767	90.3%	89.3%	85.0%	89.6%	19.6%	34.6%
Tillabery	Kollo	2,791	71.6%	72.8%	57.1%	77.8%	9.3%	20.1%
Tillabery	Ouallam	880	93.3%	88.9%	82.3%	88.6%	13.9%	29.2%
Tillabery	Say	4,011	51.0%	52.0%	39.4%	61.1%	4.2%	7.5%
Tillabery	Tera	1,836	74.1%	82.0%	82.1%	85.8%	18.8%	32.3%
Tillabery	Tillabery	70	94.9%	94.2%	82.6%	91.7%	14.8%	31.8%
Zinder	Goure	12,042	45.9%	96.3%	37.2%	54.1%	43.2%	60.0%
Zinder	Magaria	20,129	53.8%	89.5%	33.7%	70.3%	31.7%	57.9%
Zinder	Matameye	7,250	35.1%	71.2%	30.3%	64.4%	27.3%	49.4%
Zinder	Mirriah	29,168	58.9%	96.4%	34.7%	57.4%	50.1%	62.6%
Zinder	Tanout	22,733	66.1%	99.7%	58.1%	68.7%	72.7%	75.6%

Source: Authors.

Appendix Table 4. Simulated groundnut aflatoxin concentration in Niger by region for Zones of Influence only (percent of time that levels exceed 4 ppb)

			Climate of 2050				
Region	**Ground-nut hectares**	**Baseline**	**GFDL**	**HadGEM**	**IPSL**	**MIROC**	**NorES**
Dosso	5,699	37.1%	42.6%	21.5%	47.0%	6.0%	13.6%
Maradi	39,949	45.4%	83.2%	70.4%	78.7%	15.8%	32.0%
Tahoua	2,272	69.5%	83.6%	77.7%	76.1%	12.0%	20.6%
Tillabery	1,355	88.3%	87.6%	83.6%	90.6%	17.7%	32.7%
Zinder	15,047	37.0%	80.6%	29.8%	55.3%	33.2%	53.7%

Source: Authors.

Appendix Figure 3. Burkina Faso regions and provinces

Source: Natural Earth boundaries.

Appendix Table 5. Simulated groundnut aflatoxin contamination in Burkina Faso by region and province (percent of time that levels exceed 4 ppb)

Region	Province	Ground-nut hectares	Baseline	Climate of 2050 GFDL	HadGEM	IPSL	MIROC	NorES
Boucle du Mouhoun	Bale	3,029	20.9%	24.0%	20.7%	25.5%	3.9%	10.6%
Boucle du Mouhoun	Banwa	4,971	20.1%	24.6%	19.3%	21.3%	2.6%	8.3%
Boucle du Mouhoun	Kossi	5,130	37.6%	30.9%	27.8%	31.7%	3.7%	7.5%
Boucle du Mouhoun	Mouhoun	3,244	23.0%	25.8%	21.8%	24.8%	3.0%	9.6%
Boucle du Mouhoun	Nayala	3,103	31.5%	41.9%	37.8%	29.2%	2.4%	12.9%
Boucle du Mouhoun	Sourou	1,943	43.9%	51.3%	43.6%	49.5%	6.1%	11.4%
Cascades	Comoe	9,988	13.7%	15.8%	11.2%	14.1%	1.5%	6.7%
Cascades	Leraba	2,631	14.2%	14.2%	7.7%	14.8%	1.2%	5.6%
Centre-Est	Boulgou	17,398	23.6%	30.6%	20.3%	27.3%	3.6%	16.8%
Centre-Est	Koulpeogo	12,485	19.4%	22.0%	16.8%	21.7%	1.1%	10.7%
Centre-Est	Kouritenga	13,140	22.2%	19.7%	9.7%	24.6%	1.6%	10.4%
Centre-Nord	Bam	1,827	61.2%	59.6%	59.3%	58.1%	9.5%	14.2%
Centre-Nord	Namentenga	8,313	46.0%	47.1%	35.2%	45.0%	1.9%	7.4%
Centre-Nord	Sanmatenga	7,056	45.6%	49.2%	38.1%	46.2%	3.8%	6.8%
Centre-Ouest	Boulkiemde	12,549	31.9%	34.9%	26.9%	30.2%	4.0%	13.0%
Centre-Ouest	Sanguie	3,692	32.1%	42.0%	37.3%	29.4%	5.0%	16.6%
Centre-Ouest	Sissili	9,061	25.0%	34.4%	23.6%	36.2%	5.4%	11.2%
Centre-Ouest	Ziro	4,588	32.4%	33.3%	20.1%	33.8%	8.2%	11.9%
Centre-Sud	Bazega	7,797	35.5%	37.0%	27.6%	35.3%	9.3%	17.1%
Centre-Sud	Nahouri	7,264	16.9%	25.2%	16.0%	20.3%	0.7%	10.4%
Centre-Sud	Zoundweogo	4,856	17.2%	26.7%	14.7%	20.7%	2.8%	11.9%
Centre	Kadiogo	3,796	39.3%	43.5%	33.5%	38.1%	6.6%	18.8%
Est	Gnagna	28,978	47.1%	54.7%	40.4%	59.4%	2.2%	9.6%
Est	Gourma	4,529	24.8%	26.3%	15.9%	30.4%	1.8%	9.4%
Est	Komandjoari	2,416	58.8%	65.0%	50.8%	68.4%	5.3%	12.9%
Est	Kompienga	570	14.2%	24.0%	13.3%	18.4%	2.9%	9.9%
Est	Tapoa	2,358	24.6%	27.6%	15.8%	30.2%	2.5%	7.7%
Haut-Bassins	Houet	12,193	15.5%	21.6%	16.0%	19.7%	2.1%	8.6%
Haut-Bassins	Kénédougou	3,537	11.3%	21.7%	13.3%	16.2%	2.0%	6.3%
Haut-Bassins	Tuy	4,447	16.4%	19.8%	17.1%	21.8%	1.6%	7.6%
Nord	Loroum	1,910	70.2%	63.2%	66.3%	56.4%	5.0%	18.4%
Nord	Passoré	6,517	37.5%	46.3%	33.4%	38.6%	2.2%	11.4%
Nord	Yatenga	12,254	54.3%	61.5%	60.1%	57.7%	7.4%	13.3%
Nord	Zondoma	3,077	45.3%	62.4%	55.5%	61.3%	6.6%	15.2%
Plateau-Central	Ganzourgou	8,804	27.8%	27.2%	18.0%	25.5%	1.2%	6.7%
Plateau-Central	Kourweogo	2,007	44.5%	44.3%	31.3%	38.8%	4.7%	11.2%
Plateau-Central	Oubritenga	5,523	34.0%	47.4%	34.5%	40.1%	3.6%	12.4%
Sahel	Séno	639	80.0%	82.0%	66.0%	80.0%	4.0%	24.0%
Sahel	Yagha	56,481	73.7%	74.5%	66.5%	78.9%	5.9%	14.9%
Sud-Ouest	Bougouriba	1,889	14.4%	13.4%	11.5%	15.6%	2.7%	5.8%
Sud-Ouest	Ioba	4,950	18.5%	19.2%	15.3%	23.3%	2.9%	7.3%
Sud-Ouest	Noumbiel	1,389	20.4%	22.9%	20.3%	30.8%	7.7%	9.8%
Sud-Ouest	Poni	1,576	15.0%	19.6%	13.7%	18.4%	2.8%	8.4%

Source: Authors.

Appendix Table 6. Simulated rainfed maize aflatoxin contamination in Nigeria by state (percent of time that levels exceed 4 ppb)

State	Rainfed maize hectares	Baseline, (1960-1990 climate)	Climate of 2050 GFDL	HadGEM	IPSL	MIROC	NorES
Abia	47,612	9.1%	15.6%	11.8%	7.5%	11.3%	11.1%
Adamawa	156,091	7.2%	19.0%	14.3%	13.6%	12.9%	14.9%
Akwa Ibom	62,368	7.9%	15.7%	15.7%	5.5%	11.1%	8.7%
Anambra	29,537	3.3%	5.8%	7.2%	4.2%	8.9%	5.9%
Bauchi	119,335	13.9%	22.9%	12.9%	11.3%	11.7%	11.1%
Bayelsa	8,648	0.2%	1.1%	0.0%	0.0%	0.3%	0.2%
Benue	117,917	8.3%	8.1%	9.4%	8.7%	9.1%	9.4%
Borno	296,131	14.3%	29.3%	22.6%	20.4%	5.5%	13.7%
Cross River	67,911	0.8%	2.1%	1.8%	2.2%	1.4%	1.8%
Delta	81,666	5.8%	10.0%	9.9%	7.2%	8.5%	11.0%
Ebonyi	28,899	0.6%	1.3%	1.3%	0.4%	1.7%	1.4%
Edo	50,191	6.9%	10.8%	12.2%	7.7%	11.5%	9.9%
Ekiti	48,749	4.3%	12.1%	15.7%	16.0%	15.2%	10.9%
Enugu	57,637	14.3%	25.6%	23.0%	13.9%	15.7%	16.6%
Fed Cap Terr	7,500	3.4%	7.8%	6.6%	5.7%	4.0%	4.9%
Gombe	128,555	8.3%	20.9%	7.7%	8.0%	15.0%	13.1%
Imo	74,006	5.6%	8.9%	9.1%	13.1%	7.6%	7.1%
Jigawa	13,907	28.3%	58.2%	42.1%	37.1%	6.1%	27.9%
Kaduna	345,098	5.9%	6.4%	9.7%	4.4%	9.5%	9.9%
Kano	67,983	15.3%	34.0%	23.9%	22.6%	8.3%	17.3%
Katsina	137,273	10.8%	28.8%	24.8%	16.1%	4.4%	12.1%
Kebbi	34,397	8.8%	27.7%	22.3%	19.9%	1.5%	11.6%
Kogi	141,268	12.6%	20.1%	18.5%	19.7%	18.8%	14.9%
Kwara	68,787	8.5%	23.5%	21.1%	23.1%	17.3%	14.4%
Lagos	644	6.2%	9.8%	24.6%	22.1%	14.3%	17.5%
Nassarawa	68,078	4.8%	11.2%	9.2%	10.7%	5.2%	8.8%
Niger	348,197	7.9%	15.8%	11.8%	10.9%	10.0%	12.3%
Ogun	70,948	9.5%	19.8%	23.0%	24.3%	19.8%	18.2%
Ondo	85,537	5.2%	10.7%	12.0%	5.8%	12.7%	11.4%
Osun	52,601	6.1%	17.2%	20.0%	21.3%	20.5%	13.5%
Oyo	179,152	11.0%	30.2%	29.5%	36.9%	29.3%	21.2%
Plateau	172,116	5.2%	11.9%	7.3%	7.7%	5.8%	9.0%
Rivers	53,718	1.9%	5.4%	3.3%	4.7%	3.4%	2.7%
Sokoto	16,369	23.4%	45.7%	47.7%	37.6%	1.5%	22.7%
Taraba	306,136	11.7%	20.9%	17.7%	16.2%	18.6%	16.6%
Yobe	31,373	20.2%	36.2%	24.1%	24.0%	10.1%	18.2%
Zamfara	44,588	5.8%	18.7%	15.0%	10.9%	1.2%	8.2%

Source: Authors.

Appendix Table 7. Simulated rainfed maize aflatoxin contamination in Nigeria by state and Local Government Area (LGA) for Zones of Influence only (percent of time that levels exceed 4 ppb)

				Climate of 2050				
State	LGA	Rainfed maize hectares	Baseline	GFDL	HadGEM	IPSL	MIROC	NorES
Adamawa	Gombi	5,452	5.6%	28.4%	18.8%	14.8%	15.1%	17.3%
Adamawa	Hong	14,702	12.5%	17.3%	22.3%	16.7%	18.4%	17.6%
Adamawa	Song	12,758	3.1%	15.0%	9.5%	9.3%	6.8%	9.5%
Benue	Gboko	7,050	4.3%	3.3%	6.8%	3.2%	4.3%	12.9%
Benue	Konshish	4,704	0.0%	1.2%	0.7%	1.6%	0.9%	1.4%
Benue	Ushongo	4,943	2.2%	4.1%	5.1%	10.2%	3.2%	4.6%
Borno	Biu	11,641	0.3%	6.0%	0.9%	1.3%	0.1%	1.2%
Borno	Hawul	6,735	0.4%	3.0%	0.7%	0.9%	0.6%	1.7%
Borno	Kwaya Kusar	5,607	1.1%	3.7%	1.1%	1.8%	0.8%	3.1%
Cross River	Bekwarra	2,473	0.0%	6.6%	2.5%	6.0%	1.5%	6.5%
Cross River	Ogoja	6,037	1.0%	3.9%	2.3%	5.1%	2.8%	2.9%
Cross River	Yala Cross	8,773	0.2%	0.8%	0.8%	1.0%	1.1%	1.2%
Delta	Ndokwa West	7,657	9.7%	4.9%	9.4%	13.4%	8.0%	11.1%
Delta	Ughelli North	4,716	7.6%	13.8%	10.5%	6.9%	12.6%	17.3%
Ebonyi	Abakalik	2,424	0.7%	0.0%	0.9%	0.0%	1.0%	0.0%
Ebonyi	Ikwo	2,381	0.0%	0.0%	0.8%	0.0%	0.8%	0.0%
Ebonyi	Izzi	4,433	0.3%	0.0%	0.3%	0.0%	0.8%	0.5%
Gombe	Akko	23,393	9.4%	17.1%	13.2%	9.8%	16.0%	19.4%
Gombe	Dukku	26,718	7.0%	26.8%	3.6%	4.9%	11.9%	11.5%
Gombe	Kwami	12,302	7.6%	23.6%	8.9%	4.6%	17.1%	9.1%
Kaduna	Kajuru	13,474	0.6%	2.0%	3.1%	0.4%	1.5%	2.6%
Kaduna	Lere	23,148	0.0%	0.2%	0.2%	0.9%	0.0%	0.3%
Kaduna	Soba	21,021	15.7%	5.7%	20.5%	5.2%	19.1%	18.8%
Kebbi	Aleiro	544	21.0%	47.5%	38.0%	37.9%	0.7%	21.8%
Kebbi	Arewa	3,896	25.6%	52.5%	52.0%	44.9%	0.3%	21.4%
Kebbi	Argungu	1,339	13.9%	36.0%	37.3%	27.8%	0.7%	17.9%
Kebbi	BirninKe	1,302	14.2%	43.1%	32.8%	30.7%	1.9%	24.8%
Niger	Kontogur	11,086	10.5%	9.4%	12.7%	9.1%	10.5%	12.7%
Niger	Mashegu	27,637	13.3%	14.5%	16.6%	14.5%	18.5%	17.1%
Niger	Wushishi	6,901	10.1%	16.2%	14.6%	16.4%	15.2%	10.7%
Yobe	Jakusko	1,877	16.8%	46.9%	33.4%	32.3%	2.1%	19.5%
Yobe	Nangere	1,543	34.9%	25.9%	19.0%	24.1%	21.5%	30.6%

Source: Authors.

Appendix Table 8. Simulated rainfed maize aflatoxin contamination in Niger by region and department (percent of time that levels exceed 4 ppb)

				Climate of 2050				
Region	Department	Rainfed maize hectares	Baseline	GFDL	HadGEM	IPSL	MIROC	NorES
Agadez	Tchighozerine	318	82.9%	78.4%	87.6%	76.8%	3.2%	63.5%
Diffa	Diffa	3,311	43.0%	61.6%	44.8%	43.3%	1.8%	21.1%
Diffa	Mainé-Soroa	760	42.7%	66.6%	40.7%	32.1%	0.7%	28.4%
Dosso	Boboye	178	37.9%	49.4%	58.3%	55.7%	0.2%	35.8%
Dosso	Dogon-Doutchi	297	42.8%	61.1%	67.4%	58.4%	1.4%	34.0%
Dosso	Dosso	342	31.9%	53.6%	60.5%	55.7%	0.2%	31.1%
Dosso	Gaya	157	22.2%	53.9%	44.6%	44.3%	0.8%	24.5%
Dosso	Loga	127	44.1%	62.9%	67.7%	56.7%	1.3%	32.2%
Maradi	Aguie	75	24.4%	60.2%	53.4%	42.7%	0.3%	23.0%
Maradi	Dakoro	283	42.5%	68.2%	67.8%	50.5%	1.2%	32.9%
Maradi	Groumdji	134	32.4%	63.0%	67.6%	52.8%	1.1%	26.2%
Maradi	Madarounfa	85	21.4%	56.6%	55.6%	42.7%	0.5%	21.1%
Maradi	Mayahi	176	37.5%	63.2%	65.3%	48.3%	1.4%	28.4%
Maradi	Tessaoua	151	30.1%	56.2%	51.9%	42.0%	0.9%	24.1%
Niamey	Niamey	23	41.9%	59.9%	81.1%	69.9%	0.0%	37.1%
Tahoua	Bkonni	113	53.0%	66.9%	72.2%	58.1%	2.0%	38.8%
Tahoua	Bouza	134	34.2%	56.6%	65.7%	46.3%	1.0%	26.2%
Tahoua	Illela	99	53.4%	73.1%	75.2%	63.2%	2.1%	40.3%
Tahoua	Keita	62	42.7%	65.6%	68.6%	50.9%	0.8%	33.3%
Tahoua	Madaoua	168	31.0%	59.9%	62.2%	48.2%	1.6%	22.3%
Tahoua	Tahoua	175	65.1%	74.7%	82.1%	69.9%	2.8%	50.8%
Tahoua	Tchin-Tabarade	63	66.9%	79.4%	81.9%	66.1%	0.4%	49.1%
Tillabery	Filingue	60	60.0%	74.9%	73.4%	66.5%	1.7%	45.5%
Tillabery	Kollo	76	44.4%	63.0%	64.0%	59.9%	0.9%	37.3%
Tillabery	Ouallam	31	53.4%	65.2%	63.7%	60.2%	2.4%	39.0%
Tillabery	Say	132	26.2%	50.7%	51.5%	47.9%	0.1%	21.9%
Tillabery	Tera	63	47.4%	65.1%	63.6%	55.4%	1.2%	36.2%
Tillabery	Tillabery	9	63.7%	75.1%	69.9%	66.9%	3.5%	50.4%
Zinder	Goure	15	31.5%	60.7%	42.3%	33.1%	0.4%	20.3%
Zinder	Magaria	62	29.6%	55.6%	43.8%	36.8%	0.5%	20.5%
Zinder	Matameye	5	23.7%	57.5%	48.7%	43.4%	0.7%	23.6%
Zinder	Mirriah	27	35.2%	60.4%	47.2%	39.5%	1.1%	24.0%
Zinder	Tanout	25	57.5%	67.1%	68.9%	48.9%	1.0%	37.1%

Source: Authors.

Appendix Table 9. Simulated rainfed maize aflatoxin contamination in Niger by region for Zones of Influence only (percent of time that levels exceed 4 ppb)

			Climate of 2050				
Region	**Rainfed maize hectares**	**Baseline**	**GFDL**	**HadGEM**	**IPSL**	**MIROC**	**NorES**
Dosso	155	21.2%	51.6%	44.0%	40.9%	0.7%	22.9%
Maradi	227	29.4%	59.3%	63.7%	49.2%	1.2%	25.8%
Tahoua	51	50.5%	65.7%	69.7%	60.0%	1.7%	39.0%
Tillabery	39	56.3%	74.1%	69.1%	62.5%	1.9%	42.0%
Zinder	12	28.3%	60.7%	47.8%	42.0%	0.8%	25.7%

Source: Authors.

Appendix Table 10. Simulated rainfed maize aflatoxin concentration in Burkina Faso by region and province (percent of time that levels exceed 4 ppb)

				Climate of 2050				
Region	Province	Ground-nut hectares	Baseline	GFDL	HadGEM	IPSL	MIROC	NorES
Boucle du Mouhoun	Bale	19,725	6.6%	21.9%	19.7%	16.5%	5.1%	13.4%
Boucle du Mouhoun	Banwa	12,954	6.0%	15.4%	10.6%	13.2%	1.8%	9.6%
Boucle du Mouhoun	Kossi	4,294	17.4%	30.6%	27.0%	22.7%	1.8%	22.3%
Boucle du Mouhoun	Mouhoun	24,545	8.4%	20.2%	20.0%	15.2%	2.0%	11.4%
Boucle du Mouhoun	Nayala	1,344	17.8%	47.2%	60.6%	26.2%	2.2%	19.1%
Boucle du Mouhoun	Sourou	2,984	23.1%	55.4%	56.6%	35.9%	1.5%	23.2%
Cascades	Comoe	21,091	2.8%	10.4%	7.1%	5.2%	0.8%	6.2%
Cascades	Leraba	16,745	3.0%	11.9%	3.7%	4.3%	0.7%	4.8%
Centre-Est	Boulgou	9,552	9.1%	30.3%	23.2%	22.9%	3.0%	17.1%
Centre-Est	Koulpeogo	9,864	6.1%	22.3%	16.2%	16.6%	5.0%	14.7%
Centre-Est	Kouritenga	1,283	9.9%	28.8%	25.7%	26.3%	0.9%	9.6%
Centre-Nord	Bam	1,567	23.9%	52.8%	36.4%	32.8%	0.7%	23.2%
Centre-Nord	Namentenga	3,146	19.2%	44.6%	38.4%	36.3%	0.2%	12.7%
Centre-Nord	Sanmatenga	3,855	17.3%	44.4%	36.5%	32.0%	0.3%	12.0%
Centre-Ouest	Boulkiemde	3,443	13.5%	38.3%	36.3%	26.2%	3.9%	17.4%
Centre-Ouest	Sanguie	1,674	16.8%	42.5%	55.7%	26.0%	1.7%	15.4%
Centre-Ouest	Sissili	13,332	10.8%	37.6%	45.1%	28.3%	3.7%	20.6%
Centre-Ouest	Ziro	16,706	15.0%	41.5%	53.9%	32.6%	4.9%	18.8%
Centre-Sud	Bazega	4,662	18.2%	37.6%	41.1%	34.5%	4.1%	14.9%
Centre-Sud	Nahouri	2,870	4.4%	24.1%	7.5%	10.8%	1.0%	7.1%
Centre-Sud	Zoundweogo	7,677	4.5%	19.6%	13.9%	13.2%	1.8%	12.2%
Centre	Kadiogo	3,997	20.3%	49.3%	53.3%	36.2%	3.9%	15.7%
Est	Gnagna	3,829	25.1%	53.7%	53.2%	42.9%	0.4%	15.6%
Est	Gourma	11,365	11.1%	36.0%	29.4%	29.2%	1.8%	11.5%
Est	Komandjoari	900	31.6%	66.1%	66.3%	50.3%	0.4%	23.1%
Est	Kompienga	3,847	9.8%	25.7%	22.4%	14.1%	7.6%	13.0%
Est	Tapoa	6,578	11.8%	37.7%	34.3%	29.9%	1.1%	12.6%
Haut-Bassins	Houet	65,767	4.3%	12.6%	7.4%	10.4%	2.5%	8.5%
Haut-Bassins	Kénédougou	47,980	3.3%	11.2%	5.4%	7.2%	0.9%	6.1%
Haut-Bassins	Tuy	42,923	3.8%	17.0%	8.3%	11.5%	1.8%	6.9%
Nord	Loroum	2,640	26.0%	51.7%	48.7%	42.0%	1.8%	37.6%
Nord	Passoré	2,126	19.4%	49.8%	53.6%	28.0%	1.6%	15.7%
Nord	Yatenga	3,114	28.9%	60.4%	60.9%	46.5%	1.6%	26.9%
Nord	Zondoma	1,035	20.5%	59.0%	78.3%	48.4%	0.6%	18.8%
Plateau-Central	Ganzourgou	3,096	11.4%	30.6%	20.4%	23.8%	0.8%	10.7%
Plateau-Central	Kourweogo	978	22.8%	55.1%	50.7%	37.1%	2.6%	20.2%
Plateau-Central	Oubritenga	2,320	19.5%	51.4%	52.7%	40.1%	1.5%	15.9%
Sahel	Séno	8	40.0%	58.0%	54.0%	48.0%	0.0%	26.0%
Sahel	Yagha	872	35.4%	59.9%	56.3%	52.6%	2.3%	24.6%
Sud-Ouest	Bougouriba	6,900	2.4%	8.7%	5.7%	8.0%	0.0%	6.6%
Sud-Ouest	Ioba	12,918	6.3%	16.9%	10.8%	11.9%	3.3%	9.0%
Sud-Ouest	Noumbiel	3,874	10.6%	20.4%	20.3%	23.9%	4.7%	13.4%
Sud-Ouest	Poni	11,303	6.0%	15.3%	13.6%	15.3%	1.4%	10.4%

Source: Authors.

Appendix Figure 4. Guatemala departments and municipalities

Source: Natural Earth provides boundaries for nations; departments and municipalities are from GADM 2.1.

Notes: ZoIs are in orange.

Appendix Table 11. Simulated rainfed maize aflatoxin contamination in Guatemala by department (percent of time that levels exceed 4 ppb)

Department	Ground-nut hectares	Baseline, (1960-1990 climate)	Climate of 2050				
			GFDL	HadGEM	IPSL	MIROC	NorES
Alta Verapaz	98,177	4.5%	12.9%	23.5%	21.8%	4.7%	3.6%
Baja Verapaz	28,722	1.4%	0.9%	28.0%	26.8%	16.1%	14.3%
Chimaltenango	27,013	0.0%	0.0%	0.8%	2.2%	0.3%	0.5%
Chiquimula	22,144	1.7%	1.3%	39.8%	35.8%	17.4%	13.8%
El Progreso	20,248	15.3%	11.3%	52.4%	60.1%	48.8%	42.4%
Escuintla	22,635	7.6%	6.0%	40.2%	48.5%	31.8%	42.0%
Guatemala	22,648	0.4%	0.9%	9.3%	10.9%	5.4%	5.2%
Huehuetenango	47,803	4.6%	3.7%	14.1%	15.1%	5.2%	5.4%
Izabal	14,427	6.5%	9.1%	36.5%	30.8%	16.0%	9.2%
Jalapa	32,415	1.3%	0.3%	30.2%	28.6%	15.0%	15.0%
Jutiapa	69,004	1.6%	0.6%	20.5%	26.4%	12.3%	18.4%
Peten	67,823	10.5%	10.3%	68.3%	66.6%	49.2%	29.0%
Quezaltenango	46,869	5.1%	12.3%	23.7%	33.0%	19.6%	19.9%
Quiche	62,495	3.3%	2.7%	25.6%	25.7%	4.8%	5.1%
Retalhuleu	14,700	14.4%	21.7%	48.7%	36.3%	40.0%	42.1%
Sacatepequez	5,719	0.0%	0.0%	0.0%	0.5%	0.2%	0.0%
San Marcos	25,149	4.4%	9.3%	19.9%	22.7%	17.0%	19.0%
Santa Rosa	18,084	1.0%	1.3%	18.1%	29.2%	11.7%	16.9%
Solola	21,438	0.0%	0.0%	0.1%	1.1%	0.0%	0.0%
Suchitepequez	12,992	2.9%	5.6%	18.8%	19.1%	13.5%	17.6%
Totonicapan	6,007	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Zacapa	507	0.0%	1.5%	13.5%	9.1%	2.8%	0.0%

Source: Authors.

Appendix Figure 5. Honduras departments and municipalities

Source: Natural Earth provides boundaries for nations; departments and municipalities are from GADM 2.1.

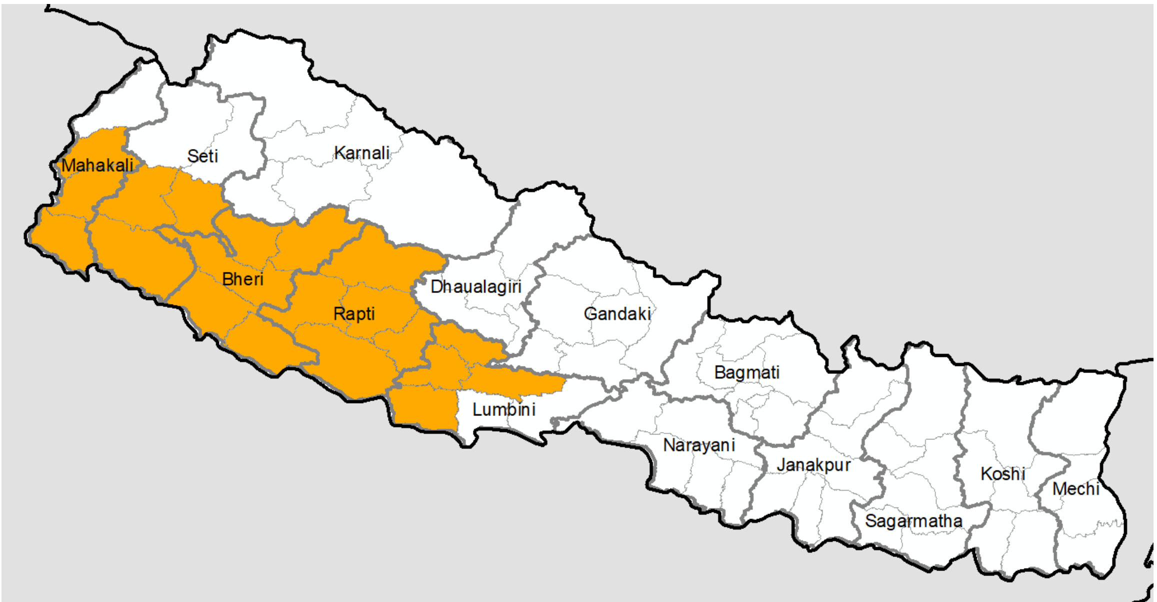
Notes: ZoIs are in orange.

Appendix Table 12. Simulated rainfed maize aflatoxin contamination in Honduras by department (percent of time that levels exceed 4 ppb)

Department	Ground-nut hectares	Baseline, (1960-1990 climate)	Climate of 2050				
			GFDL	HadGEM	IPSL	MIROC	NorES
Atlantida	20,659	23.0%	26.0%	71.9%	70.3%	78.3%	66.5%
Choluteca	17,505	6.8%	3.7%	45.4%	50.9%	51.3%	34.3%
Colon	17,728	33.9%	39.5%	70.1%	77.4%	75.3%	69.9%
Comayagua	17,444	1.4%	3.3%	28.9%	28.2%	21.5%	15.6%
Copan	19,446	0.6%	0.7%	32.7%	31.0%	15.2%	9.0%
Cortes	18,283	36.7%	33.2%	64.8%	63.8%	67.8%	60.6%
El Paraiso	18,685	5.9%	9.8%	42.4%	43.1%	41.0%	31.1%
Francisco Morazan	31,704	3.0%	4.3%	42.9%	36.9%	32.2%	25.9%
Gracias a Dios	819	8.1%	5.1%	6.3%	8.7%	4.6%	4.0%
Intibuca	5,980	0.0%	0.1%	6.6%	11.8%	2.0%	1.3%
La Paz	12,620	1.0%	0.8%	15.3%	17.3%	8.7%	6.1%
Lempira	11,717	1.3%	0.3%	7.5%	13.6%	2.3%	2.0%
Ocotepeque	5,685	0.1%	0.3%	1.0%	1.4%	0.0%	0.3%
Olancho	53,403	5.6%	10.2%	44.1%	55.4%	48.5%	36.5%
Santa Barbara	10,042	5.6%	7.8%	48.6%	52.9%	39.8%	30.3%
Valle	6,714	8.1%	6.7%	60.7%	59.0%	50.3%	36.7%
Yoro	14,526	10.2%	16.2%	49.4%	51.7%	56.5%	42.3%

Source: Authors.

Appendix Figure 6. Nepal anchal and districts



Source: Natural Earth provides boundaries for nations; anchals and districts are from GADM 2.1.

Notes: ZoIs are in orange.

Appendix Table 13. Simulated rainfed maize aflatoxin contamination in Nepal by province and anchal (percent of time that levels exceed 4 ppb)

Province	Anchal	Rainfed maize hectares	Baseline	Climate of 2050 GFDL	HadGEM	IPSL	MIROC	NorES
Central	Bagmati	48,066	0.0%	0.4%	0.5%	0.1%	0.2%	0.2%
Central	Janakpur	395	0.0%	0.0%	1.0%	1.0%	0.0%	3.9%
Central	Narayani	1,603	0.0%	0.0%	1.6%	0.8%	0.0%	1.6%
East	Koshi	612	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
East	Mechi	3,578	0.0%	0.0%	0.2%	6.7%	0.1%	0.0%
East	Sagarmatha	10,068	0.5%	0.8%	1.5%	0.7%	0.3%	3.5%
Far-Western	Mahakali	18,093	0.1%	18.1%	2.0%	9.4%	5.9%	2.1%
Far-Western	Seti	17,812	0.1%	12.5%	1.6%	11.3%	4.7%	1.5%
Mid-Western	Bheri	48,762	0.2%	20.4%	1.9%	0.0%	0.2%	0.3%
Mid-Western	Karnali	4,021	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%
Mid-Western	Rapti	26,843	0.0%	1.5%	0.1%	1.2%	0.1%	0.2%
West	Dhaualagiri	15,802	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
West	Gandaki	37,999	0.6%	1.0%	0.9%	2.6%	0.1%	0.5%
West	Lumbini	30,118	0.1%	3.6%	0.6%	0.0%	0.1%	0.2%

Source: Authors.

Appendix Table 14. Simulated rainfed maize aflatoxin contamination in Nepal by Zones of Influence (percent of time that levels exceed 4 ppb)

					Climate of 2050				
Province	Anchal	District	Rainfed maize hectares	Baseline	GFDL	HadGEM	IPSL	MIROC	NorES
Far-Western	Mahakali	Baitadi	4,117	0.0%	5.2%	0.0%	0.0%	0.0%	0.0%
Far-Western	Mahakali	Dadeldhura	4,505	0.0%	17.9%	1.0%	2.6%	2.0%	1.3%
Far-Western	Mahakali	Kanchanpur	7,922	0.2%	28.2%	3.9%	20.0%	12.3%	4.1%
Far-Western	Seti	Achham	1,588	0.0%	4.0%	0.0%	0.3%	0.1%	0.0%
Far-Western	Seti	Doti	1,228	0.0%	5.1%	0.0%	0.8%	0.0%	1.4%
Far-Western	Seti	Kailali	13,309	0.2%	15.6%	2.1%	15.0%	6.3%	1.9%
Mid-Western	Bheri	Bardiya	10,329	0.6%	29.1%	1.4%	0.0%	0.0%	0.0%
Mid-Western	Bheri	Dailekh	2,945	0.0%	1.9%	0.1%	0.1%	0.0%	0.0%
Mid-Western	Bheri	Jajarkot	1,997	0.0%	0.0%	0.0%	0.4%	0.0%	0.2%
Mid-Western	Bheri	Surkhet	11,532	0.1%	5.3%	0.3%	0.0%	0.1%	0.2%
Mid-Western	Rapti	Dang	16,218	0.0%	2.2%	0.2%	1.8%	0.1%	0.3%
Mid-Western	Rapti	Pyuthan	2,792	0.0%	1.3%	0.2%	0.0%	0.0%	0.2%
Mid-Western	Rapti	Rolpa	1,724	0.0%	0.2%	0.0%	0.0%	0.0%	0.1%
Mid-Western	Rapti	Rukum	1,516	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%
Mid-Western	Rapti	Salyan	4,593	0.0%	0.4%	0.0%	0.6%	0.0%	0.0%
West	Lumbini	Arghakhanchi	1,637	0.0%	0.8%	0.0%	0.0%	0.0%	0.1%
West	Lumbini	Gulmi	1,933	0.0%	0.2%	0.0%	0.0%	0.4%	0.3%
West	Lumbini	Kapilbastu	17,502	0.1%	5.9%	0.9%	0.0%	0.0%	0.2%
West	Lumbini	Palpa	3,819	0.0%	0.1%	0.0%	0.0%	0.3%	0.0%

Source: Authors.

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