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Climate change impacts on mycotoxin risks in US maize

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Abstract

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Keywords

climate change, maize, aflatoxins, fumonisins, deoxynivalenol

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Comments

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Climate change impacts on mycotoxin risks in US maize

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Abstract

To ensure future food security, it is crucial to understand how potential climate change scenarios will affect agriculture. One key area of interest is how climatic factors, both in the near- and the long-term future, could affect fungal infection of crops and mycotoxin production by these fungi. The objective of this paper is to review the potential impact of climate change on three important mycotoxins that contaminate maize in the United States, and to highlight key research questions and approaches for understanding this impact. Recent climate change analyses that pertain to agriculture and in particular to mycotoxigenic fungi are discussed, with respect to the climatic factors – temperature and relative humidity – at which they thrive and cause severe damage. Additionally, we discuss how climate change will likely alter the life cycles and geographic distribution of insects that are known to facilitate fungal infection of crops.

Keywords: climate change, maize, aflatoxins, fumonisins, deoxynivalenol

1. Introduction

The objective of this paper is to review the potential impact of climate change on three important mycotoxins that contaminate maize in the United States, and to highlight key research questions and approaches for understanding this impact. Mycotoxins are toxic and carcinogenic chemicals produced by fungi that infect food crops. The mycotoxins of greatest concern in US maize are aflatoxins, fumonisins, and deoxynivalenol (DON). Worldwide, mycotoxins cause a large number of diseases and human deaths annually (Liu and Wu, 2010), from liver and esophageal cancer, acute toxicosis, immune suppression, and stunted growth in children (Wild and Gong, 2010). In the US, human illness from mycotoxins has been documented in specific geographical regions. However, this is rare, because Food and Drug Administration (FDA) mycotoxin standards in food are generally enforced. Instead, US growers experience a large economic burden from crop disposal, rejection, and downgraded prices due to high mycotoxin levels. These grower losses exceed USD 1 billion annually in 2010, with maize growers bearing the largest burden of economic loss (Vardon *et al.*, 2003).

In the near future, there is reason to believe that increased climate variability associated with climate change trends may result in higher pre-harvest levels of mycotoxins in US maize, posing both economic and health risks. The fungi that produce aflatoxins and fumonisins are more likely to infect maize and produce toxins in warmer temperatures. Moreover, warmer temperatures combined with greater extremes in precipitation or drought increase plant stress, further predisposing maize to fungal infection and mycotoxin contamination. Although climate change

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may also create new challenges for the management of mycotoxin development in stored grain, the scope of this paper is limited to effects on pre-harvest mycotoxin contamination. If mycotoxin levels increase in maize due to more frequent climate extremes, US food security is threatened in at least three ways:

- Maize growers will experience even greater economic losses from discarded, rejected, or downgraded lots with excessively high mycotoxin levels; potentially putting many growers out of business and severely compromising the livelihood of others.
- Animal health – and hence livestock industries – could be compromised from higher mycotoxin concentrations in feed, either from maize-based feedstuffs or from distillers' grains with even higher mycotoxin levels than the original grain (Wu and Munkvold, 2008).
- Human health could be compromised. Currently, mycotoxin levels in our food are usually well below FDA maximum allowable limits. But in the future, even if FDA limits were strictly enforced, our food could contain mycotoxin levels much closer to those maximum allowable limits than before, with currently unknown health impacts.

Decades of research have confirmed the multiple adverse effects to humans and animals of mycotoxins found in maize. Table 1 summarises these effects.

Aflatoxins, produced by the fungi *Aspergillus flavus* and *Aspergillus parasiticus*, are among the most potent naturally occurring chemical liver carcinogens known (Groopman *et al.*, 2008). Aflatoxins can contaminate many food and feed stuffs (Bandyopadhyay *et al.*, 2007), including maize, peanuts, tree nuts, cottonseed, and various spices. For people who are chronically infected with hepatitis B or C virus, aflatoxin consumption raises by up to thirty-fold the risk of hepatocellular carcinoma (HCC; liver cancer) compared with either exposure alone (Groopman *et al.*, 2008). Acute aflatoxicosis results in severe gastrointestinal symptoms, liver damage, and even death. In recent years, hundreds of aflatoxicosis cases in Africa have been linked to consuming aflatoxin-laden maize (Lewis *et al.*, 2005). Aflatoxin exposure is also associated with immunotoxicity in humans (Jolly *et al.*, 2006; Turner *et al.*, 2003; Williams *et al.*, 2004), and with stunted growth in children caused by intestinal damage (Gong *et al.*, 2008). In many animal species, aflatoxin B_1 has induced liver tumours and has been associated with immunotoxicity, reduced weight gain and productivity, and lower egg production and eggshell quality in poultry (Bondy and Pestka, 2000).

Fumonisins, produced by the fungi *Fusarium verticillioides* and *Fusarium proliferatum*, are a group of mycotoxins that primarily contaminate maize. Epidemiological studies have associated fumonisin consumption with increased esophageal cancer risk in humans in Africa, South America, and Asia; and the African American population in Charleston, South Carolina (Marasas, 1996). Fumonisin consumption has also been linked with neural tube defects along the Texas-Mexico border (Marasas *et al.*, 2004; Missmer *et al.*, 2006). High fumonisin levels in animal feed cause the specific diseases equine leukoencephalomalacia and porcine pulmonary oedema, and a variety of other adverse effects in multiple animal species ranging from reduced weight gain and productivity to immunotoxicity (Wu and Munkvold, 2008). Recent research has associated human exposures to fumonisins in Africa with increased susceptibility to HIV (Williams *et al.*, 2010).

Deoxynivalenol (DON), also called 'vomitoxin', is produced by the fungi *Fusarium graminearum* and *Fusarium culmorum*. It causes effects ranging from gastrointestinal dysfunction (e.g. anorexia, vomiting, and nausea) to immunotoxicity and loss of productivity (Bondy and Pestka, 2000). Recent studies have elucidated mechanisms by which DON reduces immune function and weight gain in animals (Amuzie and Pestka, 2010; Bae *et al.*, 2010; Pestka, 2008), which can result in serious economic losses if DON levels

Table 1. Adverse human and animal health effects associated with three classes of mycotoxins.

	Human health effects	Animal health effects
Aflatoxins	Liver cancer (hepatocellular carcinoma) Acute aflatoxicosis Immune suppression Stunted growth in children	Liver damage Immune suppression Reduced weight gain and productivity Lower eggshell quality in poultry
Fumonisins	Esophageal cancer Neural tube defects in babies Potentially increased susceptibility to HIV	Equine leukoencephalomalacia Porcine pulmonary oedema Immune suppression Reduced weight gain and productivity
Deoxynivalenol	Gastrointestinal disorders Immune dysfunction	Gastrointestinal disorders Immune dysfunction Reduced weight gain and productivity

are high in animal feed. Evidence of toxicosis in humans is rare (Sudakin, 2003), although Chinese epidemiological studies suggest that DON may cause emetic effects in humans (Pestka and Smolinski, 2004). Studies on human intestinal cells have shown that DON can adversely affect nutrient absorption (Maresca *et al.*, 2002).

2. Background on climate change

A primary source of disagreement among scientists, policymakers, and laypersons alike is not so much whether climate change is occurring (as it would be physically impossible for climatic conditions *not* to change at all); but, rather, what the cause of recent climate change patterns is and the nature and extent of potential effects. Most scientists conclude that warming of the climate system is 'unequivocal', and that it is likely that anthropomorphic greenhouse gas emissions contribute to current warming trends (NRC, 2010). The cause of current climatic trends is not the focus of this paper. Rather, we focus on the impact of these climatic trends as they affect agriculture and food safety through the distribution of mycotoxigenic fungi. Nonetheless, it is useful to provide a brief background on climate science.

Climate change has been occurring ever since the earth was formed. Many factors have driven climate fluctuations for millennia, such as changes in the sun's energy output, slight fluctuations in the earth's orbit, volcanic eruptions, and meteor strikes. However, recent climate patterns suggest a deviation from longer-term history. Average temperatures have risen across the United States since 1901, with an increased rate of warming over the past 30 years. Seven of the top 10 warmest years on record have occurred since 1990. Average global temperatures show a similar trend; 2000-2009 was the warmest decade on record worldwide (EPA, 2010). Aside from warmer temperatures, a variety of other indicators suggest recent changes from the norm in climate patterns. These are summarised in Table 2.

The Intergovernmental Panel on Climate Change (IPCC) stated in its Fourth Assessment Report (AR4), published in 2007, that not only is warming of the climate system unequivocal, but most of the observed increase in globally averaged temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas emissions (IPCC, 2007). The IPCC, established by the World Meteorological Organization and the United Nations Environment Programme (UNEP), is the organisation that assesses the risks associated with climate change caused by human activity. The US National Academy of Sciences panel report from the America's Climate Choices suite of studies has concluded that 'a strong, credible body of scientific evidence shows that climate change is occurring … and poses significant risks for a broad range of human and natural systems' (NRC, 2010).

Climate change would have significant impacts on agriculture worldwide. Increasing temperatures of 1-3 °C are predicted to increase global agricultural production on the whole (Easterling *et al.*, 2007). The greatest increases in agricultural output in this scenario would be seen in temperate zones at middle to high latitudes. Beyond 3 °C increases in temperature, global production would be expected to decrease, particularly in the tropic and subtropic regions of the world (IPCC, 2007). Although food production might increase at the lower predicted temperature rises, there would be potential problems associated with the timing of crop planting and harvesting due to weather pattern changes, as well as a possible increase in extreme weather events affecting rainfall, pests, and plant disease (Easterling *et al.*, 2007). Aside from food quantity, food quality is also likely to change resulting from climatic shifts. One way in which future warming could compromise food safety is in the increase of microbial contaminants (Havelaar *et al.*, 2010; Tirado *et al.*, 2010). Another important way in which climate change would affect food quality is in the prevalence of mycotoxins.

3. Mycotoxigenic fungi under different climatic conditions

If the earth's surface temperatures continue in a warming trend, and other associated climate patterns may be changing, then farmers, food industries, and policymakers should be concerned about changing mycotoxin risks both in the short term and in the long term. In the short term, from year to year, temperature and precipitation may favour or discourage growth of mycotoxigenic fungi and

Table 2. Climate indicators that have shown recent change in patterns (EPA, 2010).

Weather and climate	Oceans	Snow and ice	Society and ecosystems
Global temperature	Ocean heat	Arctic sea ice	Heat-related deaths
Heat waves	Sea surface temperature	Glaciers	Length of growing season
Drought	Sea level	Lake ice	Plant hardiness zones
Global precipitation	Ocean acidity		Leaf and bloom dates
Heavy precipitation			Wildlife wintering ranges
Cyclone intensity			

mycotoxin contamination of agricultural products. In the long term, climatic trends may pose longer-term impacts on distribution of fungi, their mycotoxins, and host crop plants.

Miraglia *et al.* (2009) point out that, of the major potential impacts of climate change, food safety and food security have received relatively less attention. Agriculture is profoundly affected by the main climatic factors that may change significantly in the near future: temperature, precipitation, drought, and atmospheric carbon dioxide. A number of agricultural entities could be affected by these climatic factors, including soil quality, crop yields, and the biological environment of crops such as the abundance of pests and plant pathogens. Mycotoxins are among the foodborne risks that are dependent upon climatic conditions. Indeed, the ability of fungi to produce mycotoxins is largely influenced by temperature, relative humidity, insect attack, and stress conditions of the plants (Miraglia *et al.*, 2009). Additionally, more extreme rainfall and drought events would favour formation of DON and fumonisin, respectively (Miller, 2008).

Sanchis and Magan (2004) have summarised growth profiles, including optimal temperature and water activity for different fungal species and their corresponding toxin produced. This information is summarised in Table 3. It should be noted that these growth and production conditions may vary depending on the infected crop; and that other factors, such as temperature cycling, can have different effects on the amount of growth or toxin produced.

We focus on the potential impact of climate change to contamination of maize by aflatoxins, fumonisins, and DON.

Climate change and aflatoxin contamination

The major factors contributing to high concentrations of aflatoxins are high temperatures and drought stress. These two environmental factors directly impact maize and *A. flavus*. High temperatures and dry conditions favour growth, conidiation, and dispersal of *A. flavus* and impair growth and development of maize (Cotty and Jaime-Garcia, 2007; Diener *et al.*, 1987; McMillian *et al.*, 1985; Payne, 1985, 1992; Payne *et al.*, 1988; Scheidegger and Payne, 2003;

Table 3. Optimal growth and water availability for fungal growth and mycotoxin production (Sanchis and Magan, 2004).

	Fungal growth						
	Alternaria alternata, A. tenuissima[1]	***Aspergillus flavus, A. parasiticus***[2]	***Fusarium verticillioides, F. proliferatum***[3]	***Fusarium culmorum, F. graminearum***[4]	***Aspergillus ochraceus***[5]	***Penicillium verrucosum***[6]	***Aspergillus carbonarius***[7]
Crop/media	Wheat, tomato, sorghum, pecans, and cotton	*In vitro* medium	Maize	Cracked moist maize	Barley grains & maize-based media	Grain	Grape juice medium
a_w	0.88-0.89	0.95	>0.90	0.98-0.995	>0.80-.98	N/A	0.92-0.987
Optimal temperature (°C)	N/A[8]	35	30	20-25	30	N/A	35
Min/max (°C)	N/A	N/A	4/37	5/35	8/37	0/35	15/45
Mycotoxin production[8]	ALT, AME, AOH	aflatoxins	fumonisins	DON	OTA	OTA	OTA
a_w	>0.97	0.99	>0.93	0.99	0.98	0.90-0.95	N/A
Temperature (°C)	25	33	15-30	*F. graminearum*: 29-30 *F. culmorum*: 25-26	25-30	25	N/A
Min/max (°C)	N/A	N/A	10/37	11	N/A	N/A	N/A

[1] Adapted from Magan and Lacey (1985).
[2] Adapted from Magan and Baxter (1993).
[3] Adapted from Marin *et al.* (1999).
[4] Adapted from Magan and Lacey (1984).
[5] Adapted from Marin *et al.* (1998).
[6] Adapted from Cairns *et al.* (2003).
[7] Adapted from Mitchell *et al.* (2003) and Battilani *et al.* (2003).
[8] Abbreviations used: ALT = altenuene; AME = alternariol monomethyl ether; AOH = alternariol; DON = deoxynivalenol; OTA = ochratoxin A; N/A = not analysed.

Sétamou *et al.*, 1997; Thompson *et al.*, 1983; Widstrom, 1990, 1992, 1996, 2003).

Field, greenhouse and controlled environment studies have shown that high temperatures favour infection of maize with *A. flavus* and contribute to high concentrations of aflatoxins (Jones *et al.*, 1980; Payne *et al.*, 1985; Shearer *et al.*, 1992). In controlled environment studies, Payne *et al.* (1988) showed a striking effect of temperature on infection of maize kernels after inoculation of the silks with conidia of *A. flavus*. The day/night regime of 34/30 °C resulted in 28% of the kernels infected, whereas at the day/night regime of 26/22 °C only 2.4% of the kernels were infected.

High temperatures and low rainfall also favour production of *A. flavus* conidia and their dispersal. Shearer (1992) found soil populations of *A. flavus* in Iowa in 1988 (the worst year for recorded aflatoxin contamination in the Midwest) to average 1,200 colony forming units (cfu)/g following harvest. These populations, however, dropped to 700 and 396 cfu/g by 1989 and 1990, respectively, and to 14 cfu/g in 1991 and 0.3 cfu/g by 1993 (McGee *et al.*, 1996). Jones *et al.* (1980) found that concentrations of airborne spores were negatively associated with rainfall and hours of leaf wetness, and that ears that were pollinated during periods with high population of airborne conidia of *A. flavus* had a greater percentage of infected ears. In another study Jones *et al.* (1981) found that dry soils favour the production and dispersal of inoculum.

Soils contain diverse populations of *A. flavus* and these populations can shift from year to year. Bayman and Cotty (1991) showed that the profile of VCGs (Vegetative Compatibility Groups) of *A. flavus* can shift such that a dominant VCG one year may not be detected the next year. Temperature may contribute to shifts in population structure and high temperature has been reported to maintain aflatoxin production in *A. flavus* when cultured serially under laboratory conditions (Horn and Dorner, 2002). Sétamou *et al.* (1997) observed that the highest fraction of aflatoxin producers were in the hotter regions of Africa.

Several studies report that high soil temperature and drought stress are key environmental parameters that are positively correlated with aflatoxin contamination and increased incidence of aflatoxigenic strains or species (Horn and Dorner, 1999; Jaime-Garcia and Cotty, 2010; Orum *et al.*, 1999). Although warmer temperatures and greater extremes in precipitation (especially drought) are known to shift the balance in favour of increased aflatoxin levels, the specific population genetic processes that drive this shift are unknown. Populations of aflatoxin-producing fungi may shift in response to (1) clonal amplification that results from strong directional selection acting on a nontoxin or toxin-producing trait, (2) disruptive selection that maintains a balance of extreme toxin phenotypes, and (3) increased sexual reproduction that results in continuous distributions of toxin phenotypes.

In a preliminary study, it was found that precipitation correlates with species richness in *Aspergillus* section *Flavi*; for example, soil-inhabiting *A. parasiticus* was not cultured from soil in the wetter regions in Africa and India (Carbone *et al.*, unpublished data). However, *A. parasiticus* is abundant in southern Georgia (Horn and Greene, 1995) where it is fairly wet, which suggests that precipitation and other environmental parameters must be interpreted within the context of the underlying population genetic structure of a specific region. Previously, multilocus sequence typing (MLST) was used to genotype populations of *A. flavus* and *A. parasiticus* sampled in Georgia (Carbone *et al.*, 2007; Moore *et al.*, 2009) and recently extended to include populations in India, Argentina, Africa, and Australia. Multilocus haplotypes based on MLST minimise erroneous sampling of multiple isolates from a single clonal lineage, providing an unbiased estimate of genotypic and species diversity. These corrected genetic data can be analysed within an evolutionary and population genetic framework to distinguish variation in aflatoxin production due to genetic isolation and shared common ancestry from variation in aflatoxigenicity that is the result of temperature or other abiotic factors.

Climate change and fumonisin contamination

Major factors affecting the risk of *Fusarium* infection and subsequent fumonisin contamination are temperature, insect injury, drought stress, and water activity (determined by kernel moisture/developmental stage) (Bush *et al.*, 2004; Miller, 2001; Munkvold, 2003; Warfield and Gilchrist, 1999).

Although fumonisin-producing fungi can be found wherever maize is grown, their prevalence varies geographically, as does the risk of fumonisin contamination of grain. In maize-growing areas, fumonisin risk is typically greater at lower latitudes and altitudes, where conditions are relatively warmer than in high-latitude or high-altitude maize-growing regions. In the US, Shelby *et al.* (1994) found a highly significant negative correlation (-0.753, $P<0.001$) between latitude and fumonisin concentrations when a uniform set of maize hybrids was planted in 17 locations. In North America, fumonisin risk is higher in Texas and the south-eastern states of the US, compared to the central US; however, fumonisins remain the most common mycotoxins in the 'corn belt' states (Nebraska, Kansas, Iowa, Illinois, Indiana and Ohio). A similar pattern exists in Asia north of the Tropic of Cancer. In most of Central and South America and Southeast Asia, fumonisins are an important risk in lower-elevation maize production areas, but DON predominates at higher elevations. In Europe, fumonisin risk is higher in Italy, Spain, and southern

France. In Africa, all maize-producing areas are at risk for fumonisins, depending on altitude.

Conditions that favour fumonisin contamination of maize grain have been studied in the field and in the laboratory. The most important environmental influences on fumonisin risk are insect damage to grain and moisture stress in maize plants (Miller, 2001; Munkvold, 2003). Temperatures in most maize-producing areas are within the range conducive for *F. verticillioides* growth and fumonisin production, but the risk is higher in warmer temperate or subtropical areas or in warmer seasons in temperate areas (De la Campa *et al.,* 2005; Miller, 2001). In Ontario, Canada, fumonisins do not occur regularly, but in 1993 were present in areas with above-normal temperatures and moisture stress (Miller *et al.,* 2001). From field studies, De la Campa *et al.* (2005) described complex seasonal effects of temperature and rainfall on fumonisin concentrations in maize grain. At the time of silk initiation, temperatures between 15 and 34 °C were most favourable, but during the peak silking period, fumonisins were higher when the maximum daily temperature exceeded 34 °C. Rainfall events of >2 mm increased fumonisin concentrations if they occurred at silk initiation, but were associated with lower fumonisins if they occurred after the peak silking period. Shelby *et al.* (1994) reported a significant negative correlation (-0.779, $P<0.01$) between June rainfall and fumonisins in the multi-location in the US.

Specific information on temperature, water activity, relative humidity, and other environmental conditions required for different phases of the *F. verticillioides* life cycle, as well as fumonisin production has come from various laboratory studies. Some of these results were summarised by Maiorano *et al.* (2009). Sporulation, germination, and growth of *F. verticillioides* are optimised at 25-30 °C (Maiorano *et al.,* 2009; Rossi *et al.,* 2009). Most studies have found optimal conditions for fumonisin production are a temperature close to 30 °C and high water activity (Marin *et al.,* 1999; Reid *et al.,* 1999). However, optimal conditions for fumonisin production by *F. proliferatum* appear to be significantly different, with a lower optimal temperature (Marin *et al.,* 1999).

Infection by *Fusarium* spp. can occur directly through maize silks, through injuries caused by insects, or through systemic infection of the plant (Munkvold *et al.,* 1997). It is important to understand the relative importance of these different pathways and how temperature and other climate variables affect each infection pathway. Munkvold *et al.* (1997) and Munkvold and Carlton (1997) established that infection through silks was significantly more effective than entrance into the kernels through systemic infection of the whole plant. Transmission of the fungus from seed to plant was equally likely under a wide range of temperatures (Wilke *et al.,* 2007), but systemic transmission from plant to kernel was increased at higher temperatures (Murillo-Williams and Munkvold, 2008), which could enhance the importance of this infection pathway under warmer conditions.

More frequent climate extremes may lead to altered composition of *Fusarium* species that infect maize kernels, which, in turn, could alter the composition of mycotoxins contaminating infected kernels. In surveys in Iowa, *F. verticillioides* was predominant in southern and central Iowa, but *Fusarium subglutinans* was predominant in cooler northern Iowa (Munkvold, 2003b). *F. subglutinans* does not produce fumonisins, but does produce other mycotoxins of lower health concern, including fusaproliferin, beauvericin, and moniliformin. Moreover, *F. subglutinans* consists of at least two subgroups, designated Groups 1 and 2. In Iowa, Group 2 is predominant, and it produces fusaproliferin, but not beauvericin (Munkvold *et al.,* 2009). Fusaproliferin production, however, is favoured by cooler temperatures (Castellá *et al.,* 1999). What remains unknown is how climate changes may result in altered *Fusarium* species and subspecies composition in maize growing areas, affecting the potential for mycotoxin contamination. Therefore the impact of a changing climate on fumonisin risk will be complicated by the concomitant effects on *Fusarium* species composition attacking maize crops.

Climate change and deoxynivalenol contamination

There are several ongoing research effects to investigate the effects of weather-, crop-, and pathogen-related factors on the accumulation of DON in wheat grain, and to develop empirical and mechanistic models to predict *Fusarium* head blight (FHB) and DON in grain. These efforts have led to better insight as to factors driving DON contamination of grain (Odenbach, 2010) and the development of DON prediction models (DeWolf *et al.,* 2008; Nita *et al.*, 2008). Active and relevant areas of research have been the use of quantitative methods to evaluate the relationship between disease intensity and DON accumulation in wheat (Paul *et al.*, 2005, 2006) and model development to predict the dispersal and density of spores of *F. graminearum* within the wheat canopy based on temperature, relative humidity, and precipitation (Paul *et al.*, 2004, 2007). Similar investigations are largely lacking for the *Gibberella* ear rot (GER)-maize-DON system. In maize, the fungus invades the ear via the silk and is capable of causing substantial damage and elevated levels of DON contamination if cool, humid conditions occur during the weeks after silking. However, late infections may also occur through the base of the ear if frequent rainfall occurs late in the growing season (Payne, 1999).

Based on their trichothecene profiles, isolates of *F. graminearum* can be classified as one of three major chemotypes, 15-acetyl-deoxynivalenol (15-ADON), 3-acetyl-deoxynivalenol (3-ADON) and nivalenol (NIV), with the 15-ADON chemotype being predominant in North America and 3-ADON in South America and Europe (Gale *et al.,* 2007; Ward *et al.*, 2002). However, recent studies have shown that the frequency of 3-ADON isolates is rapidly increasing in North America, replacing the 15-ADON producers (Gale *et al.*, 2007; Puri and Zhong, 2009; Ward *et al.,* 2008). For instance, in North Dakota, 3-ADON producers made up 3% of the isolates of *F. graminearum* collected prior to 2002 and 44% of those collected in 2008 (Puri and Zhong, 2009). Similarly, Ward *et al*. (2008) reported that the frequency of 3-ADON chemotype increased substantially (14-fold) in Western Canada between 1998 and 2004. They speculated that the increased frequency may be due in part to the superior pathogenic fitness of the 3-ADON isolates in wheat over the 15-ADON isolates, since the former group has been shown to be more aggressive than the latter, producing more spores and DON and having a faster growth rate (Ali *et al*., 2009; Gale *et al.,* 2009; Puri and Zhong, 2009; Ward *et al.,* 2008). Inoculated greenhouse studies in North Dakota showed that 3-ADON isolates produced significantly more DON than the 15-ADON isolates in grain of an FHB-susceptible spring wheat variety and one of two FHB-resistant varieties evaluated (Puri and Zhong, 2009). Ward *et al.* (2008) observed a similar difference in DON accumulation between a susceptible and a moderately resistant wheat variety following inoculation with 3-ADON and 15-ADON isolates of *F. graminearum*, with DON levels being significantly higher in grain from spikes of a susceptible variety inoculated with the 3-ADON chemotype than grain from spike inoculated with 15-ADON chemotype, but not in grain from the moderately resistant cultivar. Inoculated field experiments conducted in North Dakota (Ali *et al*., 2009) and Minnesota (Gale *et al.*, 2009) showed similar results.

The role of climate change in the population shift of *F. graminearum* in the US is unknown, as is the influence of the emerging chemotype (3-ADON) on *Gibberella* ear rot (GER) and DON in maize. Controlled-environment and field studies would be beneficial in determining: (1) whether the temperature requirements are different between 3-ADON and 15-ADON isolates, and (2) whether there is a difference in saprophytic and pathogenic fitness and DON producing ability between 3-ADON and 15-ADON isolates in maize under weather conditions representative of projected climate change scenarios.

Climate change and insect pests in agriculture

Insects and other arthropods that feed on the nuts, bolls, pods or ears of crops often facilitate the establishment of mycotoxigenic fungi (Dowd *et al.,* 2003). In the US Corn Belt, dusky sap beetles, *Carpophilus lugubris,* commonly feed on mouldy overwintered maize then frequently vector *Fusarium* spp. to maize ears as the beetles feed on maize pollen and silks (Connell, 1956). These inocula set the stage for further ear contamination as insect ear feeders such as European corn borer, *Ostrinia nubilalis*, or corn earworm, *Helicoverpa zea*, injure ear tissues and facilitate the establishment of fungi. *Fusarium* spp. contamination rates of maize ears have been reported as high as 90% (Dowd, 1998).

Similar plant-insect interactions that result in mycotoxigenic fungal contaminations occur in nearly every important crop (for reviews see Dowd, 1998, 2003; Widstrom, 1979). Unfortunately higher temperatures due to climate warming are likely to exacerbate problems associated with the interactions of insects, plants and fungi and potentially could create new challenges related to altered insect population growth rates, increased insect overwintering, increased insect voltinism, altered crop-pest synchrony, and altered geographical ranges of important pest species.

Because insects are ectotherms, an increase in ambient temperature directly influences their metabolic rates, developmental rates and activity patterns (Altermatt, 2010). All these factors could lead to increased numbers of insects, increased injury to crops, higher occurrence of fungal contamination, and by extension, increased levels of mycotoxins. Yet, complexities of plant-insect food webs make it difficult to test whether warmer temperatures lead to increased herbivory; so leaf fossils with evidence of insect feeding have been used to study ecosystem changes over long time scales (Zvereva and Kozlov, 2006). A study of fossilised angiosperm leaves suggests that insect herbivory increased during an abrupt global warming event called the Paleocene-Eocene Thermal Maximum that occurred about 55.8 million years ago (Currano *et al.,* 2008). This warming event often is compared to the modern anthropogenic climate change linked to increased CO_2 (Zachos *et al.,* 2008). The leaf fossil study is the best evidence to date that suggests increased leaf herbivory from insects likely will be linked to climate warming (Currano *et al.,* 2008).

In temperate regions, insects must synchronise development and reproduction with favourable warm periods and diapause with unfavourable cold periods (Roff, 1983). Warmer winter temperatures likely will result in greater survival of insects during their overwintering period (Porter *et al.,* 1991); and higher summer temperatures with an extended duration will influence population growth and number of generations per year. It is a well established fact that in addition to day length temperature is an important factor that influences generation time (Van Dyck and Wiklund, 2002). Voltinism of the European corn borer, for example, varies from one per year in the northern Corn Belt to two or more per year in the southern Corn Belt (Showers, 1993). Two generations of *O. nubialis* per year normally occur in Iowa, but during summers with increased temperatures, occasionally a third generation occurs. There is evidence from a dataset that extends back to the mid-nineteenth century that voltinism of a significant proportion of moth and butterflies in Central Europe had increased (Altermatt, 2010). The same study showed that 44 of the 263 species evaluated had increased voltinism since 1980. These results are correlated with increased temperatures in Central Europe, especially over the past 30 years (Altermatt, 2010).

The implication for agriculture is that increased voltinism leads to higher insect populations, which increases the chances that crop economic thresholds will be exceeded due to insect injury and control measures will be needed. Another practical consequence of increased voltinism is insects often shift to an early season flight period (Forister and Shapiro, 2003; Roy and Sparks, 2000). Such a shift in crop-pest synchrony could be problematic for growers that use early or late planting dates as an integrated pest management method to control insect pests (Naranjo and Luttrell, 2009).

Perhaps the most important agricultural challenge due to global warming is altered insect ranges. There is large-scale evidence of poleward shifts in species' ranges of non-migratory butterflies in Europe (Parmesan *et al.,* 1999). Of the 35 butterfly species studied 63% have shifted ranges to the north by 35-240 km during the century; during the same time only 3% shifted to the south (Parmesan *et al.,* 1999). There is speculation that a combination of habitat loss and climate change will lead to a decline in specialist species, which will leave biological communities with fewer species that are dominated by mobile species that tend to be habitat generalist (Warren *et al.,* 2001). Many pest species are highly mobile generalist feeders, so their populations are likely to spread with climate warming.

A study investigating the impact of climate change on *O. nubilalis* in Europe estimates that with a 1-3 °C change in temperature the distribution of this maize pest would shift northward up to 1,220 km with an increase of one generation in nearly all regions where it currently occurs (Porter *et al.,* 1991). Such poleward shifts likely will have profound consequences for agriculture as pest insects expand ranges. Another factor related to geographical range expansion is insect migration. Some insect pests of maize in the US, like the fall armyworm, *Spodoptera frugiperda*, corn earworm, *H. zea*, and the black cutworm, *Agrotis ipsilon*, migrate north from southern overwintering locations (Showers, 1997). With climatic warming it is likely that at least some of these species will overwinter further north and expand their migration ranges.

Recently, there has been a shift in the species of insects feeding on maize kernels in the US. Other types of insects are important in the infection process for *F. verticillioides* in dry, warm climates. Feeding by thrips (*Frankliniella* spp.) is the key factor influencing fumonisin levels in maize grown in California (Parsons and Munkvold, 2010). Thrips are not currently a pest of maize in the US Corn Belt, but their range may be altered as a result of climate change. Climate-driven changes in insect feeding patterns will require adaptation of insect management practices that affect mycotoxin contamination.

Some of the potential problems associated with insects and climate change could be mitigated with genetically-engineered crops. There is substantial evidence that corn that expresses genes from the bacterium *Bacillus thuringiensis* (Bt) have reduced insect injury and reduced levels of fumonisins (Munkvold *et al.,* 1997, 1999; Wu, 2006; Wu *et al.,* 2004). Insect pathogens are another possible mitigating factor as warmer temperatures could influence insect infection rates. The microsporidium, *Nosema pyrausta,* for example, is an important population regulator of European corn borer (Lewis *et al.,* 2009; Onstad and Maddox, 1989).

Mycotoxin costs in the United States

Vardon *et al.* (2003) estimated the combined effects of aflatoxins, fumonisins, and DON in US crops to cost growers over USD 1 billion annually in 2010. Aside from direct crop rejection losses, an additional USD 50 million is spent annually on research related to mycotoxin research and development costs (Robens and Cardwell, 2003). Wu (2004) further estimated that losses to the US maize industry from lost export markets due to mycotoxin contamination could exceed hundreds of millions USD. Both these studies estimated losses based on rejected food and animal feed exceeding mycotoxin limits. In the future, these mycotoxin-related losses could increase under expected climate trends.

Rejection of maize for even ethanol production will increasingly be a potential source of economic loss. Wu and Munkvold (2008) estimated the health and economic impacts of a risk associated with feeding animals the co-products of maize ethanol production: When ethanol is produced from maize, the mycotoxins in the original grain become concentrated three times in the co-products (dried distillers' grains plus solubles, DDGS), which are sold to livestock industries for feed, increasing animals' mycotoxin exposure and health risks. In a case study of fumonisin's effect on swine growth, if there were complete market penetration of DDGS in swine feed with 20% inclusion and fumonisins are not controlled, losses to swine producers from weight gain reduction may reach USD 300 million annually. Currently, there is not complete market penetration, so the annual expect loss would be much lower: USD 2-18 million. The total loss due to mycotoxins in DDGS could be significantly higher due to additive or multiplicative effects of multiple mycotoxins on animal health.

Multiple mycotoxin control strategies exist, in preharvest, postharvest, and even dietary settings (Kabak *et al.,* 2006). However, their costs and efficacies vary widely (Khlangwiset and Wu, 2010). There have been efforts to assess the cost-effectiveness and feasibility of aflatoxin control methods in the US (Wu *et al.,* 2008) and in other parts of the world (Wu and Khlangwiset, 2010a,b). In the US, one strategy that has proven consistently helpful in reducing fumonisins is transgenic Bt maize (Munkvold, 2003). Bt maize's efficacy in reducing several different mycotoxins is reviewed in Wu (2007).

These studies highlight the urgency of future work to link future climate change with mycotoxin risks in US maize. Higher temperatures and extreme weather patterns have been shown to favour mycotoxin production. Understanding costs and risks of mycotoxins, as well as cost-effectiveness of interventions, is useful for future long-term planning for US food and feed security.

Prediction models for mycotoxins in maize

Quantitative, site-specific risk assessments or predictive models for mycotoxin accumulation could contribute significantly to management efficiency in maize. Some models are based on laboratory studies describing the effects of environmental conditions such as temperature and water activity on the production of mycotoxins (Marin *et al.,* 1999), and these can be used as a basis for field models. Other models are based on data collected from field studies, or developed by validating laboratory results in the field. Such models have been developed to describe or predict occurrence of aflatoxins, DON, fumonisins, or zearalenone in maize (Battilani *et al.,* 2008; De la Campa *et al.,* 2005; Maiorano *et al.,* 2009; Schaafsma and Hooker, 2007), while others describe or predict infection by various *Fusarium* species (Vigier *et al.,* 2001). Input variables for these models typically include temperature, rainfall and other weather inputs, insect populations, agronomic and sometimes economic factors. Battilani *et al.* (2008) found that higher levels of fumonisins were associated with certain agronomic practices, and a negative correlation was found between fumonisins and mid-season rainfall, strengthening the association between drought stress and fumonisins. This study did not take into account insect injury, and most (or all) fields were irrigated, so rainfall effects may have been underestimated. Battilani *et al.* (2008) also described the effects of temperature and other weather variables on various components of the *F. verticillioides* disease cycle. A similar approach was taken by Maiorano *et al.* (2009), who also included insect injury as an important predicting factor, as have most other modeling efforts; De la Campa *et al.* (2005) identified insect injury as a major predictor of fumonisins, along with high temperatures and low rainfall during the period from 2 to 8 days after silking. A model developed by Dowd (2003) for both aflatoxins and fumonisins, identified insect injury as an important factor, as well as critical temperatures and rainfall amounts.

Most of these models represent tactics that will provide an early warning for the risk of unacceptable mycotoxin levels, but depend on within-season weather data. Pre-planting management decisions require stochastic models based on agronomic factors and long-term weather forecasts and/or extensive historical data on mycotoxin occurrence. This type of model has not been developed for mycotoxins in maize. However, it is likely that this will happen in the near future, and prediction models may become widely available as risk assessment tools to assist in mycotoxin management.

4. The need for future work

A recent review article on the subject of climate change and mycotoxins concluded that 'the biggest risk with respect to mycotoxins from climate change will be found in developed countries with temperate climates' (Paterson and Lima, 2010). Currently, however, there is no information on how current and future climate trends will affect mycotoxin contamination in US maize. Mycotoxin contamination already costs US maize growers hundreds of millions USD annually; this cost will almost certainly increase with warming and climatic extremes. With increased mycotoxin levels, animal and human health in the US could face risks.

While several prediction models exist linking climatic factors to aflatoxins, fumonisins, and DON (e.g. Chauhan *et al.,* 2008; De la Campa *et al.,* 2005; Maiorano *et al.,* 2009; Rossi *et al.,* 2009; Schaafsma and Hooker, 2007), none of these was conducted in US maize. The creation of a climate-mycotoxin prediction model would enable growers and their buyers to anticipate future fungal disease occurrences and mycotoxin contamination incidents. This would allow both short-term and long-term planning of mycotoxin control and grain handling-marketing strategies that ensure economic viability as well as safe food and feed supplies.

There are at least four main areas of research that are necessary to provide useful information to policymakers about future impacts of climate change on mycotoxin risk:

1. Use available simulations of future climate scenarios at regional scales to provide guidance for climatic ranges to be tested in the laboratory and field.
2. Use already existing data, as well as perform research to provide new data, on how climatic conditions in the future influence fungal populations, insect herbivory, and ultimately mycotoxin concentrations in maize.
3. Develop and validate a model that predicts aflatoxin, fumonisin, and DON levels in maize under future climatic scenarios.

4. Determine impacts of climate change to future food security, in terms of mycotoxin-related economic and health risks.

Future climate scenarios

Multiple models can provide simulations of future climate scenarios at regional scales, which can then give guidance for climatic ranges to be tested in the laboratory and field. In the US, statewide and multi-year averages of climatic conditions are inadequate for representing the spatial and temporal nature of fungal outbreaks, as these can occur at the level of individual counties within or across states. However, databases created under the North American Regional Climate Change Assessment Program (NARCCAP, 2010) can assess probability of future occurrences of conditions favourable for fungal outbreaks on a fine geographical and time scale. This program uses six regional climate models to dynamically downscale results of four global climate models used in the IPCC 2007 report, to produce 3-hourly time series of meteorological information.

The four international global climate models and six regional climate models used in NARCCP are described on www.narccap.ucar.edu. These climate data would then provide ranges for climatic conditions until 2070 – day and night temperatures, number of days/nights above specific temperatures, precipitation, relative humidity, and soil moisture – that could be used to assess how future climatic scenarios may affect toxin levels in US maize, as well as in crops around the world.

Future mycotoxin contamination

Climatic factors have different effects on the different mycotoxin-producing fungi. Therefore, different research questions would pertain to each of the three common mycotoxins in US maize: aflatoxins (*A. flavus*), fumonisins (*F. verticillioides*), and DON (*F. graminearum*). There are also important remaining questions regarding the links among climate change, insect behaviour, and mycotoxins.

Three important questions, among others, to address relating *A. flavus* and aflatoxin production to climate change are the following:

1. What are the genomic mechanisms (e.g. copy number variation) underlying adaptation to temperature, and do these processes contribute to a relatively greater number of highly aflatoxigenic and/or pathogenic strains?
2. Are some progeny from intraspecific crosses (Horn *et al.,* 2009a,b,c) more adaptable to high temperatures, and if so, do these progeny have a genotypic and phenotypic signature? Although the occurrence of intraspecific crosses has not yet been demonstrated in nature, it is possible to set up laboratory crosses and evaluate the adaptation of progeny with different toxin producing potential and genetic background under different climate change parameters. These experiments may provide a better understanding of genotype by environment interactions in *A. flavus.*
3. What are the effects of controlled day/night temperatures on infection and aflatoxin contamination of maize ears grown under controlled day/night temperatures? Are these effects strain-specific and possibly driven by local population dynamics?

Three important questions relating *Fusarium* species and fumonisin production to climate change are the following:

1. Does temperature affects *Fusarium* species composition in maize residue?
2. What are the quantitative temperature and relative humidity/surface wetness effects on fungal infection efficiency, colonisation, and fumonisin accumulation in maize ears?
3. Do previously developed models accurately predict fumonisin levels in North American maize?

Three important questions relating *Fusarium* species and DON production to climate change are the following:

1. Is there a difference in temperature requirements for growth and DON production between 3-ADON and 15-ADON isolates of *F. graminearum*?
2. What are the effects of chemotype, moisture and temperature regimes on overwintering success of *F. graminearum*?
3. Will infection efficiency, *Gibberella* ear rot intensity, grain colonisation, and DON accumulation vary among chemotypes under the influence of different temperature regime, local weather conditions and hybrid resistance (Ali *et al.*, 2009; Gale *et al.,* 2009)?

While insects have a minor role in DON risk (Munkvold, 2003a,b), they are important in fumonisin and aflatoxin risk. Both laboratory and field studies are needed to better understand how insect life cycles and herbivory could be affected by future climate change scenarios. Laboratory studies could, among other things, examine effects of winter temperatures on overwintering of the insect pests described above, by collecting appropriate life stages of insect pests in maize, incubating them with detached maize ears in the laboratory under varying temperatures, and recording: (1) survival, (2) developmental rates through larval instar stages, and (3) kernel injury as a function of temperature. Field studies could involve infecting maize hybrids with various insect pests and examining insect injury and ear rot severity under different climatic conditions.

Future model building

The information gathered in future studies could help in the development and validation of a model that predicts aflatoxin, fumonisin, and DON levels in maize under future climatic scenarios. Laboratory and field studies could generate important data on fungal infection rates and mycotoxin levels under multiple different climate scenarios in maize-planting counties throughout the US. In addition, a database should be assembled of past pathogen outbreaks in maize (location, timing, soil conditions, climate conditions, pre-conditioning factors influencing the outbreak, etc.). The same regional climate models used for the future climate scenarios to simulate conditions over the US could be used to predict future mycotoxin outbreaks, based on 'hind-casting' from past data when mycotoxin outbreaks occurred in US maize. Previously generated models predicting individual mycotoxin levels would provide useful insights for development of the integrative model.

In conclusion, it is important to determine impacts of climate change to future US food security, in terms of mycotoxin-related economic and health risks. We expect, if current climate patterns continue in this century, aflatoxin and fumonisin concentrations in maize will likely increase, whereas DON levels will decrease. However, climate change-induced alterations in cropping patterns or shifts in pathogen populations could create new opportunities for DON risk in areas where maize currently is not grown or is a minor crop, and where new, more aggressive isolates of *F. graminearum* occur. The net effect will likely be increased economic and health risks, particularly due to increased aflatoxin concentrations in maize.

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