Perspectives on global mycotoxin issues and management from the MycoKey Maize Working Group

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Abstract: During the last decade, there have been many advances in research and technology that have greatly contributed to expanded capabilities and knowledge in detection and measurement, characterization, biosynthesis, and management of mycotoxins in maize. MycoKey, an EU-funded Horizon 2020 project, was established to advance knowledge and technology transfer around the globe to address mycotoxins impacts in key food and feed chains. MycoKey included several working groups comprised of international experts in different fields of mycotoxicology. The MycoKey Maize Working Group recently convened to gather information and strategize for the development and implementation of solutions to the maize mycotoxin problem in light of current and emerging technologies. This feature summarizes the Maize WG discussion and recommendations for addressing mycotoxin problems in maize. Discussions focused on aflatoxins, deoxynivalenol, fumonisins, and zearalenone, which are the most widespread and persistently important mycotoxins in maize. Although regional differences were recognized, there was consensus about many of the priorities for research and effective management strategies. For pre-harvest management, genetic resistance and selecting adapted maize genotypes, along with insect management, were among the most fruitful strategies identified across the mycotoxin groups. For post-harvest management, the most important practices included timely harvest, rapid grain drying, grain cleaning, and carefully managed storage conditions. Remediation practices such as optical sorting, density separation, milling, and chemical detoxification were also suggested. Future research and communication priorities included advanced breeding technologies, development of risk assessment tools, and the development and dissemination of regionally relevant management guidelines.

Introduction

Our perception of the role of mycotoxins in food and feed safety has evolved continuously since the 1960s when mycotoxins were first explicitly recognized. Hundreds of toxic fungal metabolites now have been described and many of them occur in maize. Among this myriad of mycotoxins, it has become clear that there are four types that consistently affect maize and the animals that consume it; these are aflatoxins, deoxynivalenol (DON) and its derivatives, fumonisins, and zearalenone (Munkvold et al. 2019). As a result, efforts to manage mycotoxin risks in maize have focused on these compounds and the fungi that produce them; primarily, *Aspergillus flavus* (Fig 1a), *Fusarium graminearum* (Fig 1b,c), and *Fusarium verticillioides* (Fig 1d,e, f). Ear rots caused by *F. graminearum* and related species are categorized as "Gibberella ear rot," "red ear rot," or "red fusariosis," whereas those caused by *F. verticillioides* and related species are often categorized as "Fusarium ear rot," "pink ear rot," or "pink fusariosis." Ecology, epidemiology, and management of these fungi and their toxins have been reviewed from several perspectives during the past decade (Miller et al. 2014; Munkvold 2014; Munkvold et al. 2019; Palumbo et al. 2020; Perrone and Gallo 2017). Although there are dozens of other mycotoxins and toxigenic fungal species in maize, management aimed at these three species and their toxins has effects that carry over effectively to many of the less common species and mycotoxins.

Research and outreach efforts by public and private entities and NGOs are continuously being carried out, addressing all aspects of prevention and mitigation of mycotoxin risks. Among these efforts have been several comprehensive global projects funded by the European Commission, including MycoGlobe (2004 To 2008), MycoRed (2012 To 2016), MyToolBox (2016 to 2020), and MycoKey (2016 to 2020). MycoKey (http://www.mycokey.eu/) aims at developing and testing smart, integrated, sustainable solutions and innovative tool kits to reduce the major mycotoxins in economically important food and feed chains. Specific objectives include: development and implementation of rapid, reliable, and validated detection tools for toxigenic fungi and multi-mycotoxins; integration of predictive models for aflatoxins, fumonisins, DON and zearalenone contamination in maize; translation of existing monitoring technologies into on-site/storage specific application tools for growers; and communication of mycotoxin management advice with final users. MycoKey is structured into 10 Work Packages encompassing research and communication activities across four food/feed chains (maize, wheat/barley, dried fruit, and grapes) (Fig. 2). Work Package 1 is entitled "Global Mycotoxin Knowledge" and one of the tasks for this Work Package was the establishment of Working

Groups corresponding to the four food/feed chains. This review reflects information generated by some activities of the Maize Working Group.

Global Ear Rot and Mycotoxin Issues in Maize

Although there are strong commonalities across global maize growing regions regarding the main ear rot diseases and mycotoxins, there are significant regional variations in disease severity, pathogen species composition (Table 1), mycotoxin occurrence, and management options. These variations are climate-driven as a function of latitude, elevation, and rainfall, but also driven by regional crop production and storage practices and resource availability. The magnitude and nature of mycotoxin problems also depends largely on regional differences in maize consumption patterns in the human diet. The following sections highlight the most important issues and management practices for each continent where maize is grown.

Africa - Maize is the critical staple of millions across the African continent. Maize is grown virtually in all of Africa, predominantly by smallholder farmers (Guilpart et al. 2017). In 2018, the highest maize producers in Africa were South Africa, Nigeria, Ethiopia, Egypt, and Tanzania, with 12.5, 10.2, 7.4, 7.3, and 6.0 million tons, respectively (http://www.fao.org/faostat/). Maize production has increased significantly in certain countries (e.g., Ethiopia), due to recognition of maize as a high-value food crop, improved varieties, use of fertilizers, and support of extension agents that attend the needs of farmers (Abate et al. 2015). In addition, maize is becoming an important livestock feed ingredient. For example, in Nigeria, about 2 million tons of maize are used by the poultry sector alone.

However, maize production in the African continent faces serious challenges preventing it from reaching its maximum potential (Guilpart et al. 2017). Both the productivity and the safety of maize grown in Africa is threatened by climate change (Medina et al. 2017). Diverse mycotoxins, most importantly aflatoxins and fumonisins, frequently contaminate maize throughout the value chain and this is driven by both agronomic and climatic challenges. In addition, sociological and institutional challenges in the continent also contribute to mycotoxin contamination (Ezekiel et al. 2019). Large numbers of scientific papers continuously report single or multiple mycotoxins contaminating maize produced across Africa (Mahuku et al. 2019; Misihairabgwi et al. 2019). In many cases, the detected mycotoxin concentrations are well above tolerance thresholds. Across Africa, mycotoxin contamination standards are either poorly enforced or nonexistent for several reasons that include lack of mycotoxin awareness, little to no human capacity and infrastructure for monitoring, lack of discrimination in markets, copious local markets that are difficult to sample comprehensively, and other constraints (Bandyopadhyay et al. 2016). In addition, contaminated crops that are rejected due to high mycotoxin content often are diverted to informal markets, causing higher exposure among the poor. All these challenges result in chronic mycotoxin exposure among African populations, several health disorders—sometimes death—, and loss of trade opportunities (Kamala et al. 2018; Misihairabgwi et al. 2019; Wu 2015).

There are several mycotoxin management strategies available for use in different African contexts. It is important to note that, in many cases farmers do not employ available management strategies because they are not aware of the mycotoxins, are unaware of the available technologies, or the technologies are labor- and cost-prohibitive. Management practices include adhering to recommended planting dates to avoid stress conditions, planting adapted disease-resistant hybrids, tillage practices to bury residues, rotating with non-susceptible crops, correct use of fertilizers, maintaining optimal plant densities, controlling other plant pathogens and weeds, harvest on time, rapid grain drying, avoiding mechanical and insect damage, and storing the maize at ≤13% moisture in a clean, cool, well-ventilated place with no insects (Hell and Mutegi 2011). However, in some regions, even if all recommended practices are followed, mycotoxin contamination still occurs. In Tanzania, for example, it was found that climate, soil characteristics, and geographic conditions are more likely to influence *Fusarium* communities and both fumonisin and DON levels than farming practices (Degraeve et al. 2016). Intrinsic characteristics of the maize agroecosystems coupled with unexpected events such as drought, insect attack, or flooding, have a large influence on the final mycotoxin accumulation.

Use of Bt maize in the African continent is allowed only in South Africa and Sudan (ISAAA 2017); political opposition and insufficient regulatory processes hinder its approval in other African nation . Studies conducted in South Africa have reported that insect-resistant Bt maize hybrids consistently contain significantly less fumonisin and trichothecene concentrations compared to conventional maize hybrids (Alberts et al. 2017; Pellegrino et al. 2018). However, despite its benefits, adoption of insect-resistant Bt maize by smallholder farmers in South Africa remains a challenge because of the high cost and the preference of farmers to pay for herbicide-tolerant transgenic maize hybrids (Alberts et al. 2017).

Maize germplasm with resistance to aflatoxin contamination has been identified in Nigeria (e.g., (Meseka et al. 2018), Kenya, and South Africa. The aflatoxin-resistant germplasm from Kenya and South Africa was found to be resistant to fumonisin accumulation as well (Rose et al. 2017). Other research efforts in South Africa have identified inbred lines with superior resistance to fumonisin accumulation (Small et al. 2012) and hybrids with reduced susceptibilities to both aflatoxin and fumonisin contamination have been developed (Chiuraise et al. 2016). Although germplasm with superior resistance to aflatoxin and/or fumonisin is widely being used in breeding pipelines of different organizations, significantly more efforts are needed to make improved materials reach the farmers. Additionally, biofortification (enhancement of nutritional value through genetic manuipulation) is now part of several breeding programs across Africa, including maize. Relatively recently, it was reported that certain provitamin A maize materials have reduced susceptibility to aflatoxin contamination (Suwarno et al. 2019). Large-scale use of maize germplasm with increased provitamin A may contribute to reduce aflatoxin exposure in African nations and elsewhere.

Mycotoxin-predictive models for use in Africa and elsewhere have been difficult to achieve because of large number of variables—both biotic and abiotic—that influence contamination events (Mahuku et al. 2019; Munkvold 2003c). A model developed in South Africa took into account maximum temperature and minimum humidity as determinants for fumonisin-producing fungi to infect maize grains but this was also conditioned by weather conditions after flowering and maize dough stage (Rose et al. 2018). Models should also take into account the role of diverse insects attacking the maize ears. Aflatoxin-predictive models have been developed for use in Kenya (Chauhan et al. 2015). It is unclear whether the models have reached large-scale use as decision support tools by farmers or agribusiness.

Biocontrol has become an important tactic for prevention of aflatoxins in several African nations. The International Institute of Tropical Agriculture (IITA) and the United States Department of Agriculture – Agricultural Research Service (USDA–ARS), and local national institutes have successfully adapted and improved aflatoxin biocontrol technology for use in sub-Saharan Africa under the trade name Aflasafe (Bandyopadhyay et al. 2016). Within each nation, Aflasafe product contains four native atoxigenic isolates of *A. flavus*, which contain several SNPs, deletions, or insertions in the aflatoxin biosynthesis gene cluster, preventing them from producing aflatoxins (Adhikari et al. 2016). Aflasafe products have been developed, carefully tested, and registered with national biopesticide regulatory authorities for use in maize in Nigeria, Kenya, Tanzania, Senegal, The Gambia, Burkina Faso, Ghana, Zambia, Mozambique, and Malawi (Moral et al. 2020). Products for use in another 10 nations are currently being developed. To increase production and distribution of Aflasafe, IITA has transferred the technology to public or private entities in Kenya, Nigeria, Senegal, and Tanzania, for manufacture and distribution, and to raise awareness about the aflatoxin problem and its impact on health. More transference agreements are being discussed for other countries. The use of biocontrol products to limit aflatoxin content of maize is reducing aflatoxin exposure and is resulting in increased income and trade benefits to smallholder farmers (Agbetiameh et al. 2019; Bandyopadhyay et al. 2019; Senghor et al. 2020).

Prior to storage, sorting discolored, damaged, or irregularly shaped kernels is useful to remove grains with high mycotoxin content (Matumba et al. 2015). Drying and storing grain at safe moisture levels are important challenges in Africa. Adequately drying outside of the field, off the ground and on platforms, or using solar dryers, has been shown to reduce the growth of toxigenic fungi (Hell et al. 2008; Ogunkoya et al. 2011). Packaging materials or enclosed structures for stored grain that prevent absorption of moisture or provide a controlled atmosphere (hermetic storage with high CO_2 and low O_2) have been shown to inhibit *A. flavus* growth and reduce aflatoxin production in maize (Hell and Mutegi 2011; Walker et al. 2018) . Several storage technologies have been developed that are suitable for smallholder farmers. Hermetic storage bags are becoming increasingly popular as several manufacturers are producing them, and more than a million bags have been sold in Africa. However, uptake of many other technologies has been slow due to their cost or availability (Hell and Mutegi 2011; Walker et al. 2018).

Asia - In Asia, represented by as many as 48 countries, maize is one of the most important crops for food, feed, and industrial uses, and it is an important source of income for millions of farmers. Maize ranks third after rice and wheat both in area and production. The major maize-producing countries in Asia are China, India, Indonesia, Philippines, Nepal, Thailand and Vietnam. In 2018 maize production was 257 million tons in China, 27 million tons in India, and 30 million tons in Indonesia (http://www.fao.org/faostat/). In Nepal, maize was adopted in the 17th century and by the 19th centrury was the major food grain for populations, particularly the poor, throughout the Nepal foothills (Desjardins and Busman 2006). Today Nepal produces about 2.5 million tons of maize for a population of about 28 million. Asia represents a wide range of climate zones, and mycotoxin problems are regionally variable.

Many recent studies have shown that *Fusarium* spp. are the main pathogens of corn ear rot in most temperate-zone Asian countries and regions (Table 1). In China, like other parts of the world, the most important ear rot pathogens include *F. verticillioides* and the *F. graminearum* complex, though at least 10 other species have been reported. *F. verticillioides* is mainly distributed in the provinces of Heilongjiang, Jilin, Liaoning, Inner Mongolia, Hebei, Henan, Shandong, Anhui, Sichuan, Hunan, Hubei and others, while the *F. graminearum* complex is mainly distributed in Shanxi, Shaanxi, Gansu, Yunnan and Guizhou province (Dong et al. 2015; Ren et al. 2012; Zhang et al. 2012). In Gansu Province in 2011-2012, 516 *Fusarium* isolates were identified as eight different species. The *F. graminearum* species complex was dominant in 2011, but in 2012, *F. verticillioides* was the dominant species (Guo et al. 2014).

In China, fumonisins, DON, and zearalenone are the most common mycotoxins of economic importance. (Wang et al. 2006) collected 284 maize samples from 6 provinces and measured DON contents using gas chromatography. Results showed an incidence of 67%, a range of positive samples at 10 to 3800 µg/kg, an average content of 26 µg/kg, and a mean of positive samples at 52 µg/kg for all 6 provinces. Zhang et al (2012) investigated the contamination of maize samples from three areas in eastern China by *Fusarium* and fumonisin-producing fungi as well as their fumonisin-producing potential. The results showed that both the contamination by fumonisin-producing *Fusarium* species and their fumonisin-producing potential were highest in samples from the mideastern area, and the northeastern area had the lowest incidence and concentration of fumonisin contamination. The contamination by fumonisin- producing *Fusarium* species was more serious in samples from this area than in samples from the southeastern area. About 30. 5% and 50. 9% of maize samples were positive for fumonisins with the mean levels of 175 µg/kg and 224 µg/kg in 2011 and 2012, respectively, in Gansu province (Guo et al. 2014). In India, maize poultry feed samples from Haryana were analyzed, indicating widespread prevalence of fumonisin B_1. Ninety one percent of maize samples and 84% of poultry feed samples contained fumonisin B_1, ranging from 100 to 87000 µg/kg in maize and 20 to 28000 µg/kg in poultry feed (Jindal et al. 1999). On smallholder farms in the foothills of the Himalayan Mountains of Nepal, members of the *F. graminearum* complex cause Gibberella ear rot of maize and contamination with nivalenol and DON. Gibberella ear rot of maize in Nepal is associated with a several members of the *F. graminearum* complex - mainly *F. asiaticum* and *F. meridionale*, but also *F. boothii* and a putative new lineage. *F. graminearum* sensu stricto, which dominates in maize elsewhere in Asia and worldwide, was not detected in Nepal (Desjardins and Proctor 2011). Many Nepalese maize farmers are not aware that grain contaminated with fungi also can contain toxic metabolites. As a result, farmers continue to consume the grain themselves, or use it as animal feed, leading to mycotoxicoses that are sometimes lethal.

In parts of tropical and sub-tropical Asia, maize is a dietary staple, *A. flavus* is common, and associated aflatoxins in maize are a major human health problem. For example, 6% of maize samples collected in the Philippines contained over 300 μg/kg aflatoxins. In recent surveys in several SE Asian countries, mean levels of aflatoxins in maize consistently exceeded safe limits, especially in the Philippines, Thailand, and Indonesia, where means were always above 20 μg/kg (Benkerroum 2020). In a 10-year summary of global mycotoxin data in animal feeds, the South Asia region had the second-highest mean level of aflatoxins (20 μg/kg), and the highest percentage of samples exceeding 20 μg/kg (41.1%) (Gruber-Dorninger et al. 2019). Estimates of market losses in maize due to aflatoxin xontamination in Thailand vary from approximately 7 to 100 million USD per year (Lubulwa et al. 2015). Other mycotoxins also are important in southeast Asia. A survey of zearalenone in Indonesian maize-based food and feed indicated that 32 samples (36.0%) were contaminated in a range from 5.5 to 526 μg/kg. Only one highly contaminated sample was observed in a category of home-made food samples (>500 μg/kg) and the highest percentage of contaminated samples (>85.7%) was noted in a category of poultry feed (Nuryono et al. 2005). Another survey of maize for feed in Bogor, west region of Indonesia, showed that zearalenone was detected in 21% of 52 samples in a wide range from 1 to 13,500 μg/kg (Widiastuti et al. 1988). (Aksoy et al. 2009) analyzed by ELISA the occurrence of aflatoxin B1, T-2 toxin and zearalenone in forty compound animal feed samples collected in Turkey and these mycotoxins were reported to be present in 95, 65 and 87.5% of tested samples, respectively.

In recent years, more and more attention has been paid to the breeding of maize ear rot resistant varieties in China and other parts of Asia. However, the development of maize genotypes with resistance to *Fusarium* or *Aspergillus spp.*is difficult because of polygenic inheritance, incomplete information about the underlying resistance mechanisms, and lack of highly resistant germplasm.

Numerous studies have been published describing efforts in China to develop resistance to *F. verticillioides* and *F. graminearum* in different parts of the country using various sources of germplasm, often using artificial inoculation methods (Xu et al. 2019; Zhang et al. 2019; Zou et al. 2017). In most cases, moderate levels of resistance have been identified in a subset of inbred lines or varieties, and these are being incorporated into public and private breeding programs. In some cases, the resistant phenotype in highly-resistant and highly-susceptible inbred lines was reproducible over years, while phenotypes of inbred lines with moderate resistance were largely influenced by environmental factors. In one study using a double-toothpick inoculation technique, a total of 366 maize accessions from China and abroad were evaluated for resistance against *F. verticillioides* and *F.graminearum*. A total of 90 accessions with resistance to *F. verticillioides* and 32 accessions with resistance to *F. graminearum* were found. There was no significant difference in resistance to ear rot between resources collected in China and abroad (Xu et al. 2019). Taken together, these results provided insight in genetic improvement of resistance to ear rot in maize in China.

Other management practices in Asian countries include insect management, fungicides, cultural practices, and improvement of drying and storage practices. The influence of cotton bollworm and corn borer on ear rot in corn was studied on widely grown varieties in North China. The results showed that corn borers had more effect on ear rot under conditions of high rainfall and high humidity; however, cotton bollworm had more destructive effects under conditions of low rainfall and low humidity (Wei et al. 2013). In Thailand, management has included on biological control with atoxigenic strains of *A. flavus* (Pitt et al. 2015).

Toxicity of nine fungicides to *F. verticillioides* and *F. graminearum* were tested in the lab and in the field for efficacy of control of maize ear rot in China. Difenoconazole and thiophanate-methyl showed strong toxicity against both species. Control efficacies of iprodione and Jingangmeisu (a microbial fungicide) in the field were 92.3% and 80.64%, and control efficacy of spraying fungicides after inoculation was better than that of inoculation after spraying fungicides (Sui et al. 2014).

Europe - Grain maize is grown across nearly all of Europe, with early-maturing hybrids reaching North Germany, South Scandinavia and the Moscow region where 30 years ago only silage maize was grown. Climate change and the adoption of very early maturing hybrids have aided the Nordic expansion of the crop and altered the range of mycotoxigenic species infecting grain. Yearly maize production in the European Union is variable and in 2018 69.1 million tons were produced (https://ec.europa.eu/eurostat/web/products-datasets/-/tag00093). Romania was the largest maize producer (around 28%), and together with France (17%), Hungary (12%) and Italy (10%) these four Member States covered 67% of the total European grain maize production (ec.europa.eu). Conditions vary from the humid and mostly cool Atlantic region to the strongly continental Eastern Europe to the mostly hot and dry Mediterranean area, so maize hybrids, production practices, and fungal populations are diverse. In the Mediterranean area maize is mostly irrigated, and in Central Europe droughts are frequent, so yields are highly variable, ranging from 3.5 to 12 tons/ha. The majority of maize utilization in Europe is for animal feed, with most of the remaining crop used for biofuel or processing into food ingredients.

In Europe, “red ear rot” or “red fusariosis” is mainly caused by *F. graminearum* and *F. culmorum*, and “pink ear rot” or “pink fusariosis” is caused by *F. verticillioides*, *F. proliferatum*, and *F. subglutinans*. Other species may be involved in causing both symptom types (Table 1). Both types can be found throughout Europe, but red ear rot is more predominant at higher latitudes and pink ear rot at lower latitudes (Bottalico 1998; Munkvold 2003c, 2017). Aspergillus ear rot and aflatoxins are less prevalent than *Fusarium* spp. in Europe, but can cause significant problems during outbreak years characterized by heat and drought (Battilani et al. 2013). In Hungary, aflatoxin outbreaks occurred in 2007, 2012 and 2017, with levels reaching 300 to 400 μg/kg on the most susceptible hybrids. Climate change is likely to increase aflatoxin problems throughout Europe (Battilani et al. 2016). Mycotoxin occurrence is highly variable across different geographic areas and years (Palumbo et al. 2020), and even between very close farms due to microclimatic variation (Leggieri et al. 2015).

Genetic resistance is a major component of the mycotoxin management strategy throughout Europe. In each region the optimal hybrids with resistance to toxigenic species should be identified. Highly susceptible hybrids may have serious fungal infection and toxin contamination in the absence of insect damage. Intense breeding efforts are required and the most effective programs rely on artificial inoculation-mediated selection where yield and resistance to toxigenic fungi have to be combined. A set of QTLs and candidate genes that could accelerate breeding for resistance of maize lines to *F. verticillioides* has been identified (Maschietto et al. 2017), but work is still in progress to transfer these results to farmers. Investigation of the international germplasm collection in Hungary demonstrated that there can be a very large 10-20 fold difference in resistance to individual toxigenic species among maize genotypes. Ten to 15 % of the hybrids show some resistance to the three main pathogens, while another 10-15% is highly susceptible to all three (Mesterhazy et al. 2012; Szabo et al. 2018). Because toxin sensitivity differs among animal species, hybrid choice is important and can differ based on intended end-use; the necessary hybrid database should be at hand to make the best decision. Resistance must be monitored during the registration process and the hybrids in the commercial production should be checked for resistance to the given pathogens. A similar process should be made in every maize growing area. In this way farmers can decide optimize hybrid selection and balance the different priorities.

Even though resistance has a central role, full resistance does not exist for any of the pathogens, and therefore, an integrated plant management strategy should be planned for every field. Optimizing fertilization, tillage, sowing time and seedbed quality, uniform plant stand, insecticide use, harvest and storage is necessary to maintain safety of the crop from mycotoxins (Blandino et al. 2009). In particular, management of European corn borer (*Ostrinia nubilalis*) (ECB) with insecticide treatment or transgenic Bt maize hybrids has been shown to decrease levels of fumonisins and other *Fusarium* toxins in several European countries (Blandino et al. 2010; Folcher et al. 2010; Ostry et al. 2015; Ostry et al. 2010; Pellegrino et al. 2018; Regnault-Roger et al. 2010). However, Bt maize can be planted on a limited basis only in a few European countries; in 2017, only Spain and Portugal produced Bt maize (ISAAA 2017). Because of these regulatory constraints on the planting of transgenic maize, heavy use of insecticides is required to effectively control ECB in most European countries.

Biocontrol with atoxigenic strains of *A. flavus* was considered in Italy and positive results from field trials (Mauro et al. 2018) opened the way for both giving the product to farmers with a temporary authorization and for registration, expected before 2021.

Support for farmers coming from predictive modelling (Battilani et al., 2015) has been pursued for fumonisin and aflatoxin management (Battilani et al. 2013; Battilani et al. 2003; Maiorano et al. 2009). The dynamic risk of contamination is predicted during the growing season, starting from silk emergence, and the output reports the probability of producing maize grain contaminated above the legal limit in force in Europe. Even if pre-harvest remedial actions are not available, predictions are appreciated by farmers for the harvest and the post-harvest grain management.

***North America/Central America* -** The United States is the leading maize producer in the world and the largest exporter (http://www.fao.org/faostat/). Maize production occurs to some extent in 49 of the 50 states, but its intensity is greatest in the so-called “corn belt” consisting of about 10 states in the Central US. The leading maize producing state is Iowa, with production of about 63 million tons in 2018, more than any other nation except China and Brazil. Canadian maize production is limited by climate, with annual production of about 14 million tons concentrated in the southernmost latitudes of the country. Maize produced in the US and Canada is nearly 100% commercial hybrid varieties and the majority is utilized for animal feed or ethanol production. Mexico is a significant maize-producing country and the center of origin of maize. In contrast to the US, maize production in Mexico, as in many Central American countries, involves a range of operations from large, irrigated, commercial hybrid production to households growing open-pollinated land races on small, rainfed plots for subsistence. A large proportion of maize produced in Mexico and Central America is for direct human consumption, which makes the mycotoxin issue a critical one for human health. Mycotoxins, especially fumonisins, are linked to several human health problems in this part of the world (Van der Westhuizen et al. 2013).

Occurrence of ear rots and mycotoxins in the US and Canada mimics the pattern observed for similar latitudes in Europe (Munkvold et al. 2019). The most widespread toxigenic species is *F. verticillioides* and fumonisins are the most common mycotoxins. Similar symptoms caused by *F. proliferatum, F. subglutinans*, and *F. temperatum*, are associated with fumonisins and other mycotoxins. Fumonisin contamination in the Central US is highly correlated with insect injury in the field (Munkvold 2014; Munkvold 2003b). Incidence of DON in US maize can be similar to that of fumonisins, but average contamination levels are lower for DON (Munkvold et al. 2019), and are more concentrated at higher latitudes in the US and in Canada, especially around the Great Lakes. Contamination by DON in North America is mostly associated with *F. graminearum sensu stricto*. Unsafe levels of aflatoxin contamination occur sporadically in the Central US and Canada, but aflatoxins are a chronic problem in the southern states of the US. In Central America and Mexico, *F. verticillioides* and *A. flavus* are the most important toxigenic species, and most prevention and mitigation efforts target fumonisins and aflatoxins. At higher elevations in Mexico, *F. subglutinans* becomes more important as a cause of Fusarium ear rot (Reyes-Velazquez et al. 2011).

In the US and Canada, mycotoxin management efforts focus on hybrid selection for resistance to ear rot diseases and transgenic resistance to insects (Munkvold 2014). Most widely planted commercial hybrids have partial resistance to Fusarium and Gibberella ear rots, and some have moderate partial resistance to *A. flavus*. Most resistance breeding programs are in the private sector, but public-sector breeding programs have reported significant progress toward improved resistance to Aspergillus ear rot (Womack et al. 2020), Fusarium ear rot (Holland et al. 2020; Morales et al. 2019), Gibberella ear rot (Butron et al. 2015; Kebede et al. 2016), and their associated mycotoxins. The use of multiple "stacked" insect resistance genes in commercial hybrids is standard practice, to mitigate yield losses and mycotoxin risks associated with injury by ECB and other lepidopteran insects. Populations of ECB have plummeted dramatically in the US due to the widespread planting of insect-resistant hybrids, providing significant economic benefit to maize producers and consumers (Hutchison et al. 2010). In Mexico and Central America, management practices place a greater emphasis on cultural practices and endemic resistance in land races, although commercially bred resistance is important in hybrids. Transgenic maize is not allowed in Mexico or in Central America, except for Honduras, where the majority of maize is insect-resistant (ISAAA 2017). For this reason, managing insects that promote mycotoxin contamination in this part of the world relies heavily on insecticides. Various cultural practices have been shown to influence mycotoxin levels in maize grown in North and Central America; however, implementation of these practices (or lack thereof) is often driven by economic forces that are independent of mycotoxin concerns. Thus, decisions about planting date, crop sequence, fertilization, irrigation, tillage, etc., are usually based on optimizing return on investment in terms of yield, or resource availability. On the other hand, biological control for aflatoxins using atoxigenic *A. flavus* strains has been effective and is increasingly implemented in the southern US (Isakeit 2011).

South America - In South America, maize is a major source of food used in human consumption in raw form or in maize based-products. Maize also is the main ingredient in feed intended for swine, poultry and dairy cattle. Brazil and Argentina are among the five major maize producing and exporting countries in the world. In 2018 maize production in Brazil was estimated at 82 million tons and 43 million tons in Argentina. Among the world's leading maize exporters, Brazil and Argentina occupy the second and third place, after USA, with around 29 and 24 million tons, respectively, in 2017 (http://www.fao.org/faostat/).

Both in Brazil and Argentina, maize is cultivated in different agro- ecological areas; however, the main concern related to fungal and mycotoxin contamination is due to *Fusarium* species and fumonisin contamination. *F. verticillioides* is the predominant *Fusarium* species associated with maize (Castanares et al. 2019; Iglesias et al. 2010). In Brazil, *F. verticillioides* was common throughout all geographical regions, and *F. proliferatum* and *F. subglutinans* are uncommon pathogens in maize in Brazil (Silva et al. 2017). In Argentina *F. subglutinans* was the predominant species in cold and temperate areas such as the Northwest of the country (Torres et al. 2001), and *F. temperatum* was also common in this area (Fumero et al. 2020).

Brazilian mycotoxin surveys have reported high frequencies and levels of fumonisin contamination. The second most commonly detected mycotoxin is zearalenone, present in 74-95% of maize samples (de Oliveira et al. 2009). All studies performed in maize and maize based products agreed in the low frequency of aflatoxin contamination. Low rates of contamination and levels of DON were also found (Franco et al. 2019; Oliveira et al. 2017). In Argentina a survey carried out from 1999 to 2010 showed that the percentage of maize samples contaminated by fumonisins was also between 90 and 100%. The percentages of positive samples with zearalenone and DON in maize were similar and did not exceed 10%. As was mentioned for Brazil, except in one year, aflatoxins levels were low (Garrido et al. 2012).

Other maize-producing countries in South America are, in decreasing order, Paraguay, Venezuela, Colombia and Peru with a maize production volume amounting to about 3.2 (Paraguay) to 1.5 (Peru) million tons. In these countries there have been few studies related to the presence of mycotoxins in maize; publications are limited to case reports, as in Colombia in 2005 when unusually high aflatoxin contamination occurred, affecting nearly 50,000 hectares planted with white and yellow maize, associated with an unusual precipitation pattern in the region and a pest infestation (Acuña et al. 2005).

Mycotoxin management strategies in South American maize focus on the preharvest stage. These include cultural practices, use of Bt maize, resistant hybrids, and prediction modelling. Chemical control is widely used for foliar diseases but the effectiveness of this measure for ear rot control is very inconsistent (Lanza et al. 2016).

Techniques to reduce mycotoxin levels include those associated with the control of ear rot in the field, such as the rotation of maize with non-host crops. However, common rotation schemes in Argentina are limited to two-year rotations of maize/soybean or wheat/soybean/maize (three crops in two years). In Brazil, a key driver in the expansion of maize production has been double cropping, which means planting two crops in a field in the same year, soybean in the summer (rainy season) and a winter crop of maize. Additionally, destruction of stubble, the use of disease-free seeds to prevent the further spread of the causative agents, seed treatment with fungicides, precision agriculture cropping systems with balanced fertility by use of precision fertilizer management systems are practiced to promote lower disease incidence and lower mycotoxin contamination.

Transgenic maize varieties expressing *Bacillus thuringiensis* proteins (Bt maize) have been a widely adopted alternative to insecticides and, have been the primary technology for insect control in Brazil and Argentina with approximately 85% of Brazilian maize and 87% of Argentinian maize planted with Bt traits in 2017 (ISAAA 2017). Studies have shown that Bt maize presented lower incidence of *F. verticillioides* and fumonisin levels, presumably through the reduction of insects, which act as vectors of fungi (Barros et al. 2009; de la Campa et al. 2005), although another study in Brazil found no statistical difference in fumonisin contamination between Bt and non-Bt samples (Barroso et al. 2017). Resistance to Bt maize recently has been described in Argentina and Brazil in some insect populations including *Diatraea saccharalis* (sugarcane borer) and *Spodoptera frugiperda* (fall armyworm) (Fatoretto et al. 2017; Grimi et al. 2018).

Developing and using resistant hybrids may prevent both ear rot progress and mycotoxin contamination. Although genetic variation for resistance to *Fusarium* ear rot exists among inbred lines and hybrids in field maize, there is no complete resistance to either ear rot or fumonisin accumulation.

Efforts are directed towards the search for genetic material resistant to both parameters, since the correlation between grain infection and fumonisin levels in kernels is variable (Munhoz et al. 2015). High levels of disease resistance were observed in Argentinean landraces that are being used to improve elite germplasm (Campos-Bermudez et al. 2013).

The use of models to predict fumonisin accumulation in maize may become an integrative tool; several predictive models have been proposed for *F. verticillioides* infection and fumonisin contamination by including different combinations of climatic, agronomic and maize genotype factors. In Argentina, (Sancho et al. 2018) developed weather-based logistic models as tools for estimating seasonal contamination levels, with the goal of improving kernel sampling efficiency at export terminals and mills as part of an integrated system for fumonisin management in the maize value chain.

The efficacy of bacteria antagonistic to *F. verticillioides* has been demonstrated under greenhouse and field conditions with the intention to exploit them as potential biocontrol agents suitable for widespread use in maize in Argentina. *Bacillus subtilis, Bacillus amyloliquefaciens,* and *Pseudomonas cepacia* have been used to suppress *Fusarium verticillioides*, reduce fumonisin accumulation in maize kernels, and promote plant growth (Cavaglieri et al. 2005; Pereira et al. 2011). A promising strategy to reduce aflatoxin accumulation is the biological control based on competitive exclusion; reduction of aflatoxin B_1 content in maize kernels by 54 to 83% was reported in Argentina (Alaniz Zanon et al. 2018; Camiletti et al. 2018).

MycoKey Maize Working Group – Mycotoxin Research and Management Priorities

On June 6, 2018, the Maize Working Group of the MycoKey Project met in Bucharest, Romania, to undergo a brainstorming session on the most important priorities for research and management of mycotoxins in maize. The session was guided through the use of the Nominal Group Technique, a moderated discussion approach that has been used previously to identify priorities for research and management of mycotoxin problems. (Bandyopadhyay et al. 2008; Leslie et al. 2018) focused on research ideas related to chemical detection methods, genetics and biodiversity of mycotoxins. The Nominal Group Technique is designed to generate a diversity of ideas and to facilitate equal input from all participants, as well as incorporating a ranking process. The resulting ideas and rankings are useful for identifying trends as well as novel innovations. In the Maize Working Group session, six questions, formulated by the MycoKey project leadership, were posed separately to two groups of experts from Europe, North and South America, and Africa. Questions addressed pre- and post-harvest management priorities for fumonisins, aflatoxins, DON, and zearalenone; effective decontamination/detoxification strategies; and priorities for technology development and information transfer (Suppl. Table 1). The Nominal Group Technique results in a structured discussion with five stages: 1) Silent generation of individual responses; 2) Sharing ideas, during which members of the group share their responses and all responses are recorded; 3) Idea explanation, which consists of a moderated discussion during which responses are clarified and refined; 4) Individual voting and ranking, when each participant ranks the five most important responses for the question and these ranks are collected and summarized; 5) Presentation of results, when results from the discussions are presented on a question by question basis. There were 10 participants in the Nominal Group activity, which was carried out in two iterations. First, two separate subgroups of five participants simultaneously considered each question through Stage 4; then, results were combined, Stages 2 through 4 were repeated with all 10 participants, and Stage 5 was completed. All responses are listed in Supplementary Table 1; very similar responses were combined to prepare the summary charts (Fig. 3).

Pre-harvest Management Actions

Fumonisins. When queried about the most important pre-harvest actions to limit fumonisin contamination in maize, participants identified 20 potentially effective actions, although all 20 alternatives were not mutually exclusive (Suppl. Table 1). The most highly ranked practice was maize genotype selection (Fig. 3a), incorporating the concepts of genetic resistance to infection by *F. verticillioides* or fumonisin production, and local adaptation. This practice was identified as the most important one by 50% of the working group members. The second most highly ranked practice was insect management, which was scored as the most important practice by 30% of the working group members. The third-ranking response to this question was knowledge of good agricultural practices, which combines concepts of crop management to optimize plant health with the importance of information and technology transfer to ensure implementation of these practices. Other highly ranked actions were water management (irrigation and drainage) and fertilization.

Aflatoxins. When queried about the most important pre-harvest actions to limit aflatoxin contamination in maize, participants identified 15 non-mutually exclusive actions (Suppl. Table 1). Again, maize genotype selection was the most highly ranked action (Fig. 3b), with 50% of working group members ranking it as the most important one. Biological control was ranked 2nd, with 40% considering it the most important action. The third-ranked response was irrigation/water management, followed by insect management and fertilization.

Deoxynivalenol and zearalenone. Actions for pre-harvest management of DON and zearalenone were queried in a single question, because these two toxins are typically produced by the same fungi. Eighteen responses were generated (Suppl. Table 1). Genotype selection was again the most highly ranked option (Fig. 3c), with 90% of the members ranking this action as the most important. This selection emphasized genetic resistance but also encompassed the importance of hybrid maturity class, with earlier-maturing hybrids typically having a lower risk of contamination. Crop rotation was the 2nd most highly ranked action; and crop residue management (tillage) was tied for 5th. Together these two tactics reflect the importance of the previous crop's residue as a source of inoculum for fungi in the *F. graminearum* complex. Fungicide application was ranked 3rd and insect management was ranked 4th, followed by planting date, with earlier planting in most regions resulting in a lower risk of mycotoxin contamination.

These results indicate some similarities in the approaches considered effective across the different types of mycotoxins, and also indicate some important differences. The predominance of genotype selection as an important action reflects the fact that there are many promising published studies identifying effective resistance to infection or mycotoxin production by *A. flavus*, the *F. fujikuroi* complex (primarily *F. verticillioides*), and the *F. graminearum* complex (Gaikpa and Miedaner 2019; Hawkins et al. 2018; Holland et al. 2020; Lanubile et al. 2017; Szabo et al. 2018), and it also reflects field observations of marked differences among genotypes. This option was the highest ranked one for all the mycotoxins mentioned, but it was nearly unanimously chosen as the most important action only for the toxins (DON and zearalenone) associated with the *F. graminearum* complex. This can be attributed to two main factors. Major-gene resistance has been identified for *F. graminearum*, whereas resistance to *A. flavus* and the *F. fujikuroi* complex is based on QTL with moderate effects and more complex inheritance (Mesterhazy et al. 2012; Szabo et al. 2018), thus incorporation of resistance to the *F. graminearum* complex has been more successfully implemented in commercial hybrid development. Secondly, the geographic scope of DON and zearalenone impacts is narrower than those of aflatoxins and fumonisins, and this scope is predominantly in areas of North America, Europe, and China, where maize production consists almost entirely of commercial hybrids. In contrast, aflatoxin and fumonisin impacts are widespread across areas of the developing world where maize production is a mixture of commercial hybrids and open-pollinated varieties.

Insect management was identified as an important practice for all three mycotoxin groups, but Working Group members (30%) chose it as the most important action only for fumonisins. This reflects the existing data that tie fumonisin contamination very closely with insect damage (Munkvold et al. 2019), whereas other environmental factors are more important influencers of contamination by aflatoxins, DON, or zearalenone (Fountain et al. 2014; Munkvold 2003c). Nevertheless, insect damage is universally recognized as an important factor in the epidemiology of diseases associated with most mycotoxins in maize, and reductions in aflatoxins and DON have been associated with transgenic insect protection (Folcher et al. 2012; Schaafsma et al. 2002; Yu et al. 2020).

The other practices recommended across mycotoxin groups were water management and fertilization. Water management is a complex issue in relation to mycotoxin risk; in the case of aflatoxins, drought stress is a known risk factor (Chauhan et al. 2015), whereas excess moisture is a known risk factor for infection by *F. graminearum* and subsequent DON and zearalenone contamination (Schaafsma and Hooker 2007), and fumonisin contamination is favored by drought stress followed by humid conditions (Miller 2001). From a management perspective, irrigation systems can be designed to avoid drought stress while also avoiding excess moisture in the crop canopy, especially during and after flowering, and drainage issues can be remediated, but water management continues to be a challenge in rainfed agriculture. Fertilization was mentioned as an important practice across mycotoxin groups, but was ranked no higher than 5th, indicating that overall plant health is a component of mycotoxin risk, and proper plant nutrition is one factor that can contribute to reducing the risk.

One of the most striking differences in recommendations for effective management actions is related to biological control, which was ranked very highly for aflatoxin management but was not mentioned in relation to the other mycotoxins. Application of atoxigenic strains of *A. flavus* to suppress aflatoxin contamination has been research extensively and implemented widely in North America and Africa. This approach has been very successful (Bandyopadhyay et al. 2016), but analogous efforts to successfully suppress *Fusarium* mycotoxins with atoxigenic strains have not been pursued.

Crop rotation and crop residue management were ranked as relatively important practices for DON and zearalenone, but not for aflatoxins or fumonisins. This reflects some differences in the biology of the fungi involved. *A. flavus* and *F. verticillioides* are ubiquitous occupants of the agricultural landscape, and they produce vast numbers of airborne conidia that can travel long distances. As a result, crop residue management in individual fields has little impact. *Fusarium graminearum* spreads by rain-splashed macroconidia from in-field residues, and by airborne ascospores and macroconidia that can be dispersed over long distances. Reducing in-field inoculum sources can be valuable, but the impacts of crop rotation and residue management are limited by the scale of maize and wheat production contributing to regional atmospheric inoculum (Ponte et al. 2003).

Fungicide applications were ranked as an important practice only in relation to managing DON and zearalenone. Although fungicides are not widely used to manage mycotoxins in maize, they are commonly used to manage DON contamination in small grain cereals, and this success has stimulated similar interest in maize. Research on prevention of *F. graminearum* infection by protecting susceptible silks with fungicides has shown promise (Limay-Rios and Schaafsma 2018).

Post-harvest Management and Processing/Decontamination Actions

Questions were posed to the Working Group to assess the most effective post-harvest management and processing or decontamination actions for all mycotoxins. There were 21 responses for postharvest management and 21 responses for processing and decontamination, some of which overlapped with post-harvest management responses (Suppl. Table 1). There was less consensus in these results than in the pre-harvest results. The most highly ranked post-harvest management action was rapid grain drying, which included elements of transportation logistics from the field and the actual drying method (Fig. 3d); 30% of Working Group members ranked this as the most important practice. The 2nd most highly ranked action was grain cleaning or sorting, to remove damaged/contaminated kernels; 20% of Working Group members ranked this as the most important practice. The use of good harvesting and grain handling equipment was ranked 3rd; only 10% of members ranked it as most important, but others ranked it 2nd or 3rd. This practice focuses on preventing grain damage during harvest and handling. Good storage facilities and harvest timing tied for 4th rank, both with 20% of members ranking them as most important. Harvesting at the proper time also was included as a response in the pre-harvest management query, illustrating the wide recognition of this approach as a way to prevent elevated mycotoxin levels that can occur if maize remains in the field, drying naturally. The 5th-ranked response was control of relative humidity and temperature in storage; 20% ranked it as most important. This response is somewhat confounded with the storage facilities response, considering that "good" storage facilities should include sanitation, exclusion of pests, and some level of environmental control.

For the processing and decontamination question, the highest ranking response was optical sorting (Fig 3e). Although only 10% of Working Group members ranked it as most important, several others ranked it highly. Optical sorting has repeatedly been demonstrated to be effective at removing mycotoxin-contaminated maize kernels from a moving grain stream (Pearson et al. 2004; Stasiewicz et al. 2017), although the use of this technology for this purpose is largely limited to human food uses in industrialized countries. The 2nd highest ranking response was removal of fine material through sizing or sieving operations. This was ranked highest by 30% of members. This response is very similar to the grain cleaning/sorting response that also ranked 2nd in the post-harvest management actions. The 3rd-ranking response was density separation, with 30% of members ranking it as most important. All three of these top responses are related to different physical methods of identifying and separating damaged grain and other material from healthy grain. The 4th ranked response was milling, which allows for the separation of the more contaminated components of the grain (such as the pericarp) from the typically less-contaminated components such as endosperm and embryo. Chemical detoxification ranked 5th; this category includes various approaches including ozone treatment, nixtamalization, ammoniation, and others, but does not include adsorbent materials, which was a separate response that ranked 6th.

Research/Information Needs

Finally, the Working Group responded to a question about the most pressing needs for new research and information that will most effectively contribute to improvements in mycotoxin management or reduction in risk. Twenty-six responses were generated (Suppl. Table 1). The top-ranked response was the category of “risk assessment tools,” which included the development of risk maps, real-time and long-term prediction models, and guidelines for susceptibility of maize genotypes (Fig. 3f). These ideas were ranked as most important by 40% of the Working Group members. The 2nd-highest ranking response was improved breeding technologies, including the development of transgenes, the use of genome editing, and improved knowledge about the relationship between genetic resistance and toxin accumulation. The 3rd-ranking ("geo-referenced management guidelines") and 4th-ranking ("information transfer") responses both relate to the effective communication of existing and new best practices for mycotoxin management. Collectively, these two responses were ranked as most important by 50% of Working Group members. The 5th-ranked response was improvement in technology availability/adoption. This response refers to the role of biotechnology in the battle against mycotoxins in maize; including tools such as transgenic insect protection (already available but not globally adopted), biotechnology-derived resistance to infection or mycotoxin production, or bio-engineered in-plant detoxification mechanisms (not yet available).

Conclusion

The safety of maize as a food and feed component is challenged everywhere across the globe. The four major mycotoxin groups (aflatoxins, DON and related trichothecenes, fumonisins, and zearalenone) that threaten the maize supply are common to all maize-producing areas, but their relative importance and the severity of the challenge are geographically dependent. The MycoKey Maize Working Group has served to guide research and management priorities, and their recommendations emphasize the importance of genetic resistance, insect management, grain drying and cleaning methods, and the development of risk assessment tools that account for the impacts of climate change on evolving mycotoxin risks in maize. As warming climate increases the risk of several mycotoxins, higher levels of resistance and well adapted cultural practices can contribute to sustainable production with reduced mycotoxin levels.

Acknowledgements

The Maize Working Group meeting and the contributions of several authors were supported by the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No. 678781 (MycoKey project). Funding support also was provided by GINOP-2.2.1-15-2016-00021 EU/Hungarian project and the Hungarian National innovation project TUDFO/5157/2019/ITM. The authors are grateful to Roberta Palumbo (UNICATT) for recording the session.

Literature Cited

Abate, T., Shiferaw, B., Menkir, A., Dagne, W., Kebede, Y., Kindie, T., Kassie, M., Gezahegn, B., Berhanu, T., and Tolera, K. 2015. Factors that transformed maize productivity in Ethiopia. Food Security 7:965-981.

Acuña, C., Díaz, G., and Espitia, M. 2005. Aflatoxinas en maíz: Reporte de caso en la Costa Atlántica Colombiana. Rev. Med. Vet. Zoot. 52:156-162.

Adhikari, B. N., Bandyopadhyay, R., and Cotty, P. J. 2016. Degeneration of aflatoxin gene clusters in Aspergillus flavus from Africa and North America. Amb Express 6.

Agbetiameh, D., Ortega-Beltran, A., Awuah, R. T., Atehnkeng, J., Islam, M.-S., Callicott, K. A., Cotty, P. J., and Bandyopadhyay, R. 2019. Potential of Atoxigenic Aspergillus flavus Vegetative Compatibility Groups Associated With Maize and Groundnut in Ghana as Biocontrol Agents for Aflatoxin Management. Frontiers in Microbiology 10.

Aksoy, A., Yavuz, O., Das, Y. K., Guvenc, D., and Muglali, O. H. 2009. Occurrence of Aflatoxin B1, T-2 Toxin and Zearalenone in Compound Animal Feed. Journal of Animal and Veterinary Advances 8:403-407.

Alaniz Zanon, M. S., Paz Clemente, M., and Noemi Chulze, S. 2018. Characterization and competitive ability of non-aflatoxigenic Aspergillus flavus isolated from the maize agro-ecosystem in Argentina as potential aflatoxin biocontrol agents. International Journal of Food Microbiology 277:58-63.

Alberts, J. F., Lilly, M., Rheeder, J. P., Burger, H. M., Shephard, G. S., and Gelderblom, W. C. A. 2017. Technological and community-based methods to reduce mycotoxin exposure. Food Control 73:101-109.

Bandyopadhyay, R., Frederiksen, R. A., and Leslie, J. F. 2008. Priorities for mycotoxin research in Africa identified by using the nominal group technique. Pages 19–26 in: Mycotoxins: Detection Methods, Management, Public Health and Agricultural Trade. J. F. Leslie, R. Bandyopadhyay and A. Visconti, eds. CABI, Kew, UK.

Bandyopadhyay, R., Atehnkeng, J., Ortega-Beltran, A., Akande, A., Falade, T. D. O., and Cotty, P. J. 2019. "Ground-Truthing" Efficacy of Biological Control for Aflatoxin Mitigation in Farmers' Fields in Nigeria: From Field Trials to Commercial Usage, a 10-Year Study. Frontiers in Microbiology 10.

Bandyopadhyay, R., Ortega-Beltran, A., Akande, A., Mutegi, C., Atehnkeng, J., Kaptoge, L., Senghor, A. L., Adhikari, B. N., and Cotty, P. J. 2016. Biological control of aflatoxins in Africa: current status and potential challenges in the face of climate change. World Mycotoxin Journal 9:771-789.

Barros, G., Magnoli, C., Reynoso, M. M., Ramirez, M. L., Farnochi, M. C., Torres, A., Dalcero, M., Sequeira, J., Rubinstein, C., and Chulze, S. 2009. Fungal and mycotoxin contamination in Bt maize and non-Bt maize grown in Argentina. World Mycotoxin Journal 2:53-60.

Barroso, V. M., Rocha, L. O., Reis, T. A., Reis, G. M., Duarte, A. P., Michelotto, M. D., and Correa, B. 2017. Fusarium verticillioides and fumonisin contamination in Bt and non-Bt maize cultivated in Brazil. Mycotoxin Research 33:121-127.

Battilani, P., Rossi, V., and Pietri, A. 2003. Modelling Fusarium verticillioides infection and fumonisin synthesis in maize ears. Aspects of Applied Biology:91-100.

Battilani, P., Leggieri, M. C., Rossi, V., and Giorni, P. 2013. AFLA-maize, a mechanistic model for Aspergillus flavus infection and aflatoxin B-1 contamination in maize. Computers and Electronics in Agriculture 94:38-46.

Battilani, P., Toscano, P., Van der Fels-Klerx, H. J., Moretti, A., Leggieri, M. C., Brera, C., Rortais, A., Goumperis, T., and Robinson, T. 2016. Aflatoxin B-1 contamination in maize in Europe increases due to climate change. Scientific Reports 6.

Benkerroum, N. 2020. Aflatoxins: producing-molds, structure, health issues and incidence in southeast Asian and Sub-Saharan African countries. International Journal of Environmental Research and Public Health 17.

Blandino, M., Saladini, M. A., Alma, A., and Reyneri, A. 2010. Pyrethroid Application Timing to Control European Corn Borer (Lepidoptera: Crambidae) and Minimize Fumonisin Contamination in Maize Kernels. Cereal Research Communications 38:75-82.

Blandino, M., Reyneri, A., Vanara, F., Tamietti, G., and Pietri, A. 2009. Influence of agricultural practices on Fusarium infection, fumonisin and deoxynivalenol contamination of maize kernels. World Mycotoxin Journal 2:409-418.

Bottalico, A. 1998. Fusarium diseases of cereals: Species complex and related mycotoxin profiles, in Europe. Journal of Plant Pathology 80:85-103.

Butron, A., Reid, L. M., Santiago, R., Cao, A., and Malvar, R. A. 2015. Inheritance of maize resistance to gibberella and fusarium ear rots and kernel contamination with deoxynivalenol and fumonisins. Plant Pathology 64:1053-1060.

Camiletti, B. X., Moral, J., Asensio, C. M., Torrico, A. K., Lucini, E. I., Gimenez-Pecci, M. d. l. P., and Michailides, T. J. 2018. Characterization of argentinian endemic Aspergillus flavus isolates and their potential use as biocontrol agents for mycotoxins in maize. Phytopathology 108:818-828.

Campos-Bermudez, V. A., Fauguel, C. M., Tronconi, M. A., Casati, P., Presello, D. A., and Andreo, C. S. 2013. Transcriptional and Metabolic Changes Associated to the Infection by Fusarium verticillioides in Maize Inbreds with Contrasting Ear Rot Resistance. Plos One 8.

Castanares, E., Martinez, M., Cristos, D., Rojas, D., Lara, B., Stenglein, S., and Dinolfo, M. I. 2019. Fusarium species and mycotoxin contamination in maize in Buenos Aires province, Argentina. European Journal of Plant Pathology 155:1265-1275.

Cavaglieri, L., Orlando, J., and Etcheverry, M. 2005. In vitro influence of bacterial mixtures on Fusarium verticillioides growth and fumonisin B-1 production: effect of seeds treatment on maize root colonization. Letters in Applied Microbiology 41:390-396.

Chauhan, Y., Tatnell, J., Krosch, S., Karanja, J., Gnonlonfin, B., Wanjuki, I., Wainaina, J., and Harvey, J. 2015. An improved simulation model to predict pre-harvest aflatoxin risk in maize. Field Crops Research 178:91-99.

Chiuraise, N., Derera, J., Yobo, K. S., Magorokosho, C., Nunkumar, A., and Qwabe, N. F. P. 2016. Progress in stacking aflatoxin and fumonisin contamination resistance genes in maize hybrids. Euphytica 207:49-67.

de la Campa, R., Hooker, D. C., Miller, J. D., Schaafsma, A. W., and Hammond, B. G. 2005. Modeling effects of environment, insect damage, and Bt genotypes on fumonisin accumulation in maize in Argentina and the Philippines. Mycopathologia 159:539-552.

de Oliveira, T. R., Jaccoud-Filho, D. d. S., Henneberg, L., Michel, M. D., Demiate, I. M., Barbosa Pinto, A. T., Machinski Junior, M., and Barana, A. C. 2009. Maize (Zea Mays L) Landraces from the Southern Region of Brazil: Contamination by Fusarium sp, Zearalenone, Physical and Mechanical Characteristics of the Kernels. Brazilian Archives of Biology and Technology 52:11-16.

Degraeve, S., Madege, R. R., Audenaert, K., Kamala, A., Ortiz, J., Kimanya, M., Tiisekwa, B., De Meulenaer, B., and Haesaert, G. 2016. Impact of local pre-harvest management practices in maize on the occurrence of Fusarium species and associated mycotoxins in two agro-ecosystems in Tanzania. Food Control 59:225-233.

Desjardins, A. E., and Busman, M. 2006. Mycotoxins in developing countries: A case study of maize in Nepal. Mycotoxin research 22:92-95.

Desjardins, A. E., and Proctor, R. H. 2011. Genetic diversity and trichothecene chemotypes of the Fusarium graminearum clade isolated from maize in Nepal and identification of a putative new lineage. Fungal Biology 115:38-48.

Dong, H., Wang, D., Wang, L., Liu, K., Jiang, Y., Xu, X., and Zuo, C. 2015. SCAR type detection of Fusarium graminearum clade species complex on spring maize producing areas of north China. Journal of Northeast Agricultural University 46:23-28.

Ezekiel, C., Ortega-Beltran, A., and Bandyopadhyay, R. 2019. The need for integrated approaches to address food safety risk: the case of mycotoxins in Africa. in: First FAO/WHO/AU International Food Safety Conference, Addis Ababa, Ethiopia.

Fatoretto, J. C., Michel, A. P., Silva Filho, M. C., and Silva, N. 2017. Adaptive Potential of Fall Armyworm (Lepidoptera: Noctuidae) Limits Bt Trait Durability in Brazil. Journal of Integrated Pest Management 8.

Folcher, L., Weissenberger, A., and Delos, M. 2012. Quantitative relationships between Ostrinia nubilalis activity and deoxynivalenol contamination in French maize. International Journal of Pest Management 58:302-309.

Folcher, L., Delos, M., Marengue, E., Jarry, M., Weissenberger, A., Eychenne, N., and Regnault-Roger, C. 2010. Lower mycotoxin levels in Bt maize grain. Agronomy for Sustainable Development 30:711-719.

Fountain, J. C., Scully, B., Ni, X. Z., Kemerait, R. C., Lee, R. D., Chen, Z. Y., and Guo, B. Z. 2014. Environmental influences on maize-Aspergillus flavus interactions and aflatoxin production. Frontiers in Microbiology 5:7.

Franco, L. T., Petta, T., Rottinghaus, G. E., Bordin, K., Gomes, G. A., and Oliveira, C. A. F. 2019. Co-occurrence of mycotoxins in maize food and maize-based feed from small-scale farms in Brazil: a pilot study. Mycotoxin Research 35:65-73.

Fumero, M. V., Villani, A., Susca, A., Haidukowski, M., Cimmarusti, M. T., Toomajian, C., Leslie, J. F., Chulze, S. N., and Moretti, A. 2020. Fumonisin and Beauvericin Chemotypes and Genotypes of the Sister Species Fusarium subglutinans and Fusarium temperatum. Applied and environmental microbiology.

Gaikpa, D. S., and Miedaner, T. 2019. Genomics-assisted breeding for ear rot resistances and reduced mycotoxin contamination in maize: methods, advances and prospects. Theoretical and Applied Genetics 132:2721-2739.

Garrido, C. E., Hernandez Pezzani, C., and Pacin, A. 2012. Mycotoxins occurrence in Argentina's maize (Zea mays L.), from 1999 to 2010. Food Control 25:660-665.

Grimi, D. A., Parody, B., Ramos, M. L., Machado, M., Ocampo, F., Willse, A., Martinelli, S., and Head, G. 2018. Field-evolved resistance to Bt maize in sugarcane borer (Diatraea saccharalis) in Argentina. Pest Management Science 74:905-913.

Gruber-Dorninger, C., Jenkins, T., and Schatzmayr, G. 2019. Global mycotoxin occurrence in feed: a ten-year survey. Toxins 11.

Guilpart, N., Grassini, P., van Wart, J., Yang, H., van Ittersum, M. K., van Bussel, L. G. J., Wolf, J., Claessens, L., Leenaars, J. G. B., and Cassman, K. G. 2017. Rooting for food security in Sub-Saharan Africa. Environmental Research Letters 12.

Guo, C., Wei, H. Y., Guo, M. K., He, S. Q., Jin, S. L., Chen, H. M., Wang, X. M., and Guo, J. G. 2014. Isolation, identification and biological characteristics of Fusarium verticillioides from maize ear rot samples in Gansu Province. Acta Phytopathologica Sinica 44:17-25.

Hawkins, L. K., Warburton, M. L., Tang, J. D., Tomashek, J., Oliveira, D. A., Ogunola, O. F., Smith, J. S., and Williams, W. P. 2018. Survey of Candidate Genes for Maize Resistance to Infection by Aspergillus flavus and/or Aflatoxin Contamination. Toxins 10:10.

Hell, K., and Mutegi, C. 2011. Aflatoxin control and prevention strategies in key crops of Sub-Saharan Africa. African Journal of Microbiology Research 5:459-466.

Hell, K., Fandohan, P., Ranajit, B., Kiewnick, S., Sikora, R., and Cotty, P. J. 2008. Pre- and postharvest management of aflatoxin in maize: an African perspective. Mycotoxins: detection methods, management, public health and agricultural trade:219-229.

Holland, J., Marino, T., Manching, H., and Wisser, R. 2020. Genomic prediction for resistance to Fusarium ear rot and fumonisin contamination in maize. Crop Science.

Hutchison, W. D., Burkness, E. C., Mitchell, P. D., Moon, R. D., Leslie, T. W., Fleischer, S. J., Abrahamson, M., Hamilton, K. L., Steffey, K. L., Gray, M. E., Hellmich, R. L., Kaster, L. V., Hunt, T. E., Wright, R. J., Pecinovsky, K., Rabaey, T. L., Flood, B. R., and Raun, E. S. 2010. Areawide Suppression of European Corn Borer with Bt Maize Reaps Savings to Non-Bt Maize Growers. Science 330:222-225.

Iglesias, J., Presello, D. A., Botta, G., Lori, G. A., and Fauguel, C. M. 2010. AGGRESSIVENESS OF FUSARIUM SECTION LISEOLA ISOLATES CAUSING MAIZE EAR ROT IN ARGENTINA. Journal of Plant Pathology 92:205-211.

ISAAA. 2017. Global status of commercialized biotech/GM crops in 2017: biotech crop adoption surges as economic benefits accumulate in 22 Years. ISAAA, Ithaca, NY.

Isakeit, T. 2011. PREVENTION OF AFLATOXIN CONTAMINATION OF CORN USING AF-36 OR AFLA-GUARD. Texas Agri-Life Extension Service; Texas A&M University, College Station, TX.

Jindal, N., Mahipal, S. K., and Rottinghaus, G. E. 1999. Occurrence of fumonisin B-1 in maize and poultry feeds in Haryana, India. Mycopathologia 148:37-40.

Kamala, A., Shirima, C., Jani, B., Bakari, M., Sillo, H., Rusibamayila, N., De Saeger, S., Kimanya, M., Gong, Y. Y., Simba, A., and Invest, T. 2018. Outbreak of an acute aflatoxicosis in Tanzania during 2016. World Mycotoxin Journal 11:311-320.

Kebede, A. Z., Woldemariam, T., Reid, L. M., and Harris, L. J. 2016. Quantitative trait loci mapping for Gibberella ear rot resistance and associated agronomic traits using genotyping-by-sequencing in maize. Theoretical and Applied Genetics 129:17-29.

Lanubile, A., Maschietto, V., Borrelli, V. M., Stagnati, L., Logrieco, A. F., and Marocco, A. 2017. Molecular Basis of Resistance to Fusarium Ear Rot in Maize. Frontiers in Plant Science 8:13.

Lanza, F. E., Zambolim, L., da Costa, R. V., da Silva, D. D., Vieira Queiroz, V. A., Parreira, D. F., Mendes, S. M., Coelho Souza, A. G., and Cota, L. V. 2016. Fungicide leaf application and incidence of kernel rot and total fumonisins in corn. Pesquisa Agropecuaria Brasileira 51:638-646.

Leggieri, M. C., Bertuzzi, T., Pietri, A., and Battilani, P. 2015. Mycotoxin occurrence in maize produced in Northern Italy over the years 2009-2011: focus on the role of crop related factors. Phytopathologia Mediterranea 54:212-221.

Leslie, J. F., Lattanzio, V., Audenaert, K., Battilani, P., Cary, J., Chulze, S. N., De Saeger, S., Gerardino, A., Karlovsky, P., Liao, Y. C., Maragos, C. M., Meca, G., Medina, A., Moretti, A., Munkvold, G., Mule, G., Njobeh, P., Pecorelli, I., Perrone, G., Pietri, A., Palazzini, J. M., Proctor, R. H., Rahayu, E. S., Ramirez, M. L., Samson, R., Stroka, J., Sulyok, M., Sumarah, M., Waalwijk, C., Zhang, Q., Zhang, H., and Logrieco, A. F. 2018. MycoKey Round Table Discussions of Future Directions in Research on Chemical Detection Methods, Genetics and Biodiversity of Mycotoxins. Toxins 10:19.

Limay-Rios, V., and Schaafsma, A. W. 2018. Effect of Prothioconazole Application Timing on Fusarium Mycotoxin Content in Maize Grain. Journal of Agricultural and Food Chemistry 66:4809-4819.

Lubulwa, G. A. S., Siriacha, P., Markwell, P. J., and Pitt, J. I. 2015. Estimating the burden of market loss due to aflatoxins in maize: methods and estimates for Thailand. World Mycotoxin Journal 8:459-464.

Mahuku, G., Nzioki, H. S., Mutegi, C., Kanampiu, F., Narrod, C., and Makumbi, D. 2019. Pre-harvest management is a critical practice for minimizing aflatoxin contamination of maize. Food Control 96:219-226.

Maiorano, A., Reyneri, A., Sacco, D., Magni, A., and Ramponi, C. 2009. A dynamic risk assessment model (FUMAgrain) of fumonisin synthesis by Fusarium verticillioides in maize grain in Italy. Crop Protection 28:243-256.

Maschietto, V., Colombi, C., Pirona, R., Pea, G., Strozzi, F., Marocco, A., Rossini, L., and Lanubile, A. 2017. QTL mapping and candidate genes for resistance to Fusarium ear rot and fumonisin contamination in maize. Bmc Plant Biology 17.

Matumba, L., Van Poucke, C., Ediage, E. N., Jacobs, B., and De Saeger, S. 2015. Effectiveness of hand sorting, flotation/washing, dehulling and combinations thereof on the decontamination of mycotoxin-contaminated white maize. Food Additives and Contaminants Part a-Chemistry Analysis Control Exposure & Risk Assessment 32:960-969.

Mauro, A., Garcia-Cela, E., Pietri, A., Cotty, P. J., and Battilani, P. 2018. Biological Control Products for Aflatoxin Prevention in Italy: Commercial Field Evaluation of Atoxigenic Aspergillus flavus Active Ingredients. Toxins 10.

Medina, A., Akbar, A., Baazeem, A., Rodriguez, A., and Magan, N. 2017. Climate change, food security and mycotoxins: Do we know enough? Fungal Biology Reviews 31:143-154.

Meseka, S., Williams, W. P., Warburton, M. L., Brown, R. L., Augusto, J., Ortega-Beltran, A., Bandyopadhyay, R., and Menkir, A. 2018. Heterotic affinity and combining ability of exotic maize inbred lines for resistance to aflatoxin accumulation. Euphytica 214.

Mesterhazy, A., Lemmens, M., and Reid, L. M. 2012. Breeding for resistance to ear rots caused by Fusarium spp. in maize - a review. Plant Breeding 131:1-19.

Miller, J. D. 2001. Factors that affect the occurrence of fumonisin. Environmental Health Perspectives 109:321-324.

Miller, J. D., Schaafsma, A. W., Bhatnagar, D., Bondy, G., Carbone, I., Harris, L. J., Harrison, G., Munkvold, G. P., Oswald, I. P., Pestka, J. J., Sharpe, L., Sumarah, M. W., Tittlemier, S. A., and Zhou, T. 2014. Mycotoxins that affect the North American agri-food sector: state of the art and directions for the future. World Mycotoxin Journal 7:63-82.

Misihairabgwi, J. M., Ezekiel, C. N., Sulyok, M., Shephard, G. S., and Krska, R. 2019. Mycotoxin contamination of foods in Southern Africa: A 10-year review (2007-2016). Critical Reviews in Food Science and Nutrition 59:43-58.

Moral, J., Garcia-Lopez, M. T., Camiletti, B. X., Jaime, R., Michailides, T. J., Bandyopadhyay, R., and Ortega-Beltran, A. 2020. Present status and perspective on the future use of aflatoxin biocontrol products. Agronomy 10.

Morales, L., Zila, C. T., Mejia, D. E. M., Arbelaez, M. M., Balint-Kurti, P. J., Holland, J. B., and Nelson, R. J. 2019. Diverse Components of Resistance to Fusarium verticillioides Infection and Fumonisin Contamination in Four Maize Recombinant Inbred Families. Toxins 11.

Munhoz, A. T., de Carvalho, R. V., Querales, P. J., Goncalves, F. P., and Aranha Camargo, L. E. 2015. Relationship between resistance of tropical maize inbred lines for resistance to ear rot and fumonisins accumulation caused by Fusarium verticillioides. Summa Phytopathologica 41:144-148.

Munkvold, G. 2014. Crop Management Practices to Minimize the Risk of Mycotoxins Contamination in Temperate-Zone Maize. Pages 59-77 in: Mycotoxin Reduction in Grain Chains. J. F. Leslie and A. F. Logrieco, eds. Blackwell Science Publ, Oxford.

Munkvold, G. P. 2003a. Mycotoxins in corn - occurrence, impact, and management.

Munkvold, G. P. 2003b. Cultural and genetic approaches to managing mycotoxins in maize. Annual Review of Phytopathology 41:99-116.

Munkvold, G. P. 2003c. Epidemiology of Fusarium diseases and their mycotoxins in maize ears. European Journal of Plant Pathology 109:705-713.

Munkvold, G. P. 2017. Fusarium Species and Their Associated Mycotoxins. Pages 51-106 in: Mycotoxigenic Fungi: Methods and Protocols, vol. 1542. A. Moretti and A. Susca, eds. Springer, Dordrecht.

Munkvold, G. P., Arias, S., Taschl, I., and Gruber-Dorninger, C. 2019. Mycotoxins in Corn: Occurrence, Impacts, and Management.

Nuryono, N., Noviandi, C. T., Bohm, J., and Razzazi-Fazeli, E. 2005. A limited survey of zearalenone in Indonesian maize-based food and feed by ELISA and high performance liquid chromatography. Food Control 16:65-71.

Ogunkoya, A., Ukoba, K., and Olunlade, B. 2011. Development of a low cost solar dryer. Pacific Journal of Science and Technology 12:98–101.

Oliveira, M. S., Rocha, A., Sulyok, M., Krska, R., and Mallmann, C. A. 2017. Natural mycotoxin contamination of maize (Zea mays L.) in the South region of Brazil. Food Control 73:127-132.

Ostry, V., Malir, F., and Pfohl-Leszkowicz, A. 2015. Comparative data concerning aflatoxin contents in Bt maize and non-Bt isogenic maize in relation to human and animal health - a review. Acta Veterinaria Brno 84:47-53.

Ostry, V., Ovesna, J., Skarkova, J., Pouchova, V., and Ruprich, J. 2010. A review on comparative data concerning Fusarium mycotoxins in Bt maize and non-Bt isogenic maize. Mycotoxin research 26:141-145.

Palumbo, R., GONÇALVES, A., GKRILLAS, A., LOGRIECO, A., DORNE, J.-L., Dall'Asta, C., VENÂNCIO, A., and BATTILANI, P. 2020. Mycotoxins in maize: mitigation actions, with a chain management approach. Phytopathologia Mediterranea 59:113-135.

Pearson, T. C., Wicklow, D. T., and Pasikatan, M. C. 2004. Reduction of aflatoxin and fumonisin contamination in yellow corn by high-speed dual-wavelength sorting. Cereal Chemistry 81:490-498.

Pellegrino, E., Bedini, S., Nuti, M., and Ercoli, L. 2018. Impact of genetically engineered maize on agronomic, environmental and toxicological traits: a meta-analysis of 21 years of field data. Scientific Reports 8.

Pereira, P., Ibanez, S. G., Agostini, E., and Etcheverry, M. 2011. Effects of maize inoculation with Fusarium verticillioides and with two bacterial biocontrol agents on seedlings growth and antioxidative enzymatic activities. Applied Soil Ecology 51:52-59.

Perrone, G., and Gallo, A. 2017. Aspergillus Species and Their Associated Mycotoxins. Mycotoxigenic Fungi: Methods and Protocols 1542:33-49.

Pitt, J. I., Manthong, C., Siriacha, P., Chotechaunmanirat, S., and Markwell, P. J. 2015. Studies on the biocontrol of aflatoxin in maize in Thailand. Biocontrol Science and Technology 25:1070-1091.

Ponte, E. M. d., Shah, D. A., and Bergstrom, G. C. 2003. Spatial patterns of Fusarium head blight in New York wheat fields suggest role of airborne inoculum. Plant Health Progress:1-8.

Regnault-Roger, C., Folcher, L., Delos, M., Jarry, M., Weissenberger, A., and Eychenne, N. 2010. Bt maize: a tool for improving food safety of grains at harvest. Julius-Kuhn-Archiv:553-559.

Ren, X., Zhu, Z. D., Li, H. J., Duan, C. X., and Wang, X. M. 2012. SSR marker development and analysis of genetic diversity of Fusarium verticillioides isolated from maize in China. Scientia Agricultura Sinica 45:52-66.

Reyes-Velazquez, W. P., Figueroa-Gomez, R. M., Barberis, M., Reynoso, M. M., Rojo, F. G. A., Chulze, S. N., and Torres, A. M. 2011. Fusarium species (section Liseola) occurrence and natural incidence of beauvericin, fusaproliferin and fumonisins in maize hybrids harvested in Mexico. Mycotoxin research 27:187-194.

Rose, L., Okoth, S., Flett, B., Janse van Rensburg, B., and Viljoen, A. 2018. Preharvest management strategies and their impact on mycotoxigenic fungi and associated mycotoxins. in: Mycotoxins – Socio-Economic and Health Impact as Well as Pre- and Postharvest Management Strategies.

Rose, L. J., Okoth, S., Beukes, I., Ouko, A., Mouton, M., Flett, B. C., Makumbi, D., and Viljoen, A. 2017. Determining resistance to Fusarium verticillioides and fumonisin accumulation in African maize inbred lines resistant to Aspergillus flavus and aflatoxins. Euphytica 213.

Sancho, A. M., Moschini, R. C., Filippini, S., Rojas, D., and Ricca, A. 2018. Weather-based logistic models to estimate total fumonisin levels in maize kernels at export terminals in Argentina. Tropical Plant Pathology 43:99-108.

Schaafsma, A. W., and Hooker, D. C. 2007. Climatic models to predict occurrence of Fusarium toxins in wheat and maize. International Journal of Food Microbiology 119:116-125.

Schaafsma, A. W., Hooker, D. C., Baute, T. S., and Illincic-Tamburic, L. 2002. Effect of Bt-corn hybrids on deoxynivalenol content in grain at harvest. Plant Disease 86:1123-1126.

Senghor, L. A., Ortega-Beltran, A., Atehnkeng, J., Callicott, K. A., Cotty, P. J., and Bandyopadhyay, R. 2020. The Atoxigenic Biocontrol Product Aflasafe SN01 Is a Valuable Tool to Mitigate Aflatoxin Contamination of Both Maize and Groundnut Cultivated in Senegal. Plant Disease 104:510-520.

Silva, J. J., Viaro, H. P., Ferranti, L. S., Oliveira, A. L. M., Ferreira, J. M., Ruas, C. F., Ono, E. Y. S., and Fungaro, M. H. P. 2017. Genetic structure of Fusarium verticillioides populations and occurrence of fumonisins in maize grown in Southern Brazil. Crop Protection 99:160-167.

Small, I. M., Flett, B. C., Marasas, W. F. O., McLeod, A., Stander, M. A., and Viljoen, A. 2012. Resistance in Maize Inbred Lines to Fusarium verticillioides and Fumonisin Accumulation in South Africa. Plant Disease 96:881-888.

Stasiewicz, M. J., Falade, T. D. O., Mutuma, M., Mutiga, S. K., Harvey, J. J. W., Fox, G., Pearson, T. C., Muthomi, J. W., and Nelson, R. J. 2017. Multi-spectral kernel sorting to reduce aflatoxins and fumonisins in Kenyan maize. Food Control 78:203-214.

Sui, Y., Xiao, S., Dong, X., Xue, C., and Chen, J. 2014. Toxicity and field control effect of nine fungicides against Fusarium ear rot. Journal of Maize Sciences 22:145-149.

Suwarno, W. B., Hannok, P., Palacios-Rojas, N., Windham, G., Crossa, J., and Pixley, K. V. 2019. Provitamin A Carotenoids in Grain Reduce Aflatoxin Contamination of Maize While Combating Vitamin A Deficiency. Frontiers in Plant Science 10.

Szabo, B., Toth, B., Toldine, E. T., Varga, M., Kovacs, N., Varga, J., Kocsube, S., Palagyi, A., Bagi, F., Budakov, D., Stojsin, V., Lazic, S., Bodroza-Solarov, M., Colovic, R., Bekavac, G., Purar, B., Jockovic, D., and Mesterhazy, A. 2018. A New Concept to Secure Food Safety Standards against Fusarium Species and Aspergillus Flavus and Their Toxins in Maize. Toxins 10.

Torres, A. M., Reynoso, M. M., Rojo, F. G., Ramirez, M. L., and Chulze, S. N. 2001. Fusarium species (section Liseola) and its mycotoxins in maize harvested in northern Argentina. Food Additives and Contaminants Part a-Chemistry Analysis Control Exposure & Risk Assessment 18:836-843.

Udomkun, P., Wiredu, A. N., Nagle, M., Mueller, J., Vanlauwe, B., and Bandyopadhyay, R. 2017. Innovative technologies to manage aflatoxins in foods and feeds and the profitability of application - A review. Food Control 76:127-138.

Van der Westhuizen, L., Shephard, G. S., Gelderblom, W. C. A., Torres, O., and Riley, R. T. 2013. Fumonisin biomarkers in maize eaters and implications for human disease. World Mycotoxin Journal 6:223-232.

Walker, S., Jaime, R., Kagot, V., and Probst, C. 2018. Comparative effects of hermetic and traditional storage devices on maize grain: Mycotoxin development, insect infestation and grain quality. Journal of Stored Products Research 77:34-44.

Wang, Q., Wang, J., Yu, F., Zhu, X., Zaleta-Rivera, K., and Du, L. 2006. Mycotoxin fumonisins: health impacts and biosynthetic mechanism. Prog Nat Sci 16:7-15.

Wei, T., Zhu, W., Pang, M., Liu, Y., Wang, Z., and Dong, J. 2013. Influence of the damage of cotton bollworm and corn borer to ear rot

in corn. Journal of Maize Sciences 21:116-123.

Widiastuti, R., Maryam, R., Blaney, B. J., Salfina, and Stoltz, D. R. 1988. CYCLOPIAZONIC ACID IN COMBINATION WITH AFLATOXINS, ZEARALENONE AND OCHRATOXIN-A IN INDONESIAN CORN. Mycopathologia 104:153-156.

Womack, E. D., Williams, W. P., Windham, G. L., and Xu, W. 2020. Mapping Quantitative Trait Loci Associated With Resistance to Aflatoxin Accumulation in Maize Inbred Mp719. Frontiers in Microbiology 11.

Wu, F. 2015. Global impacts of aflatoxin in maize: trade and human health. World Mycotoxin Journal 8:137-142.

Xu, J., Jiang, Y., Qin, P., Liu, K. J., Lan, S., and Xu, X. 2019. Test for ear rot resistance against F*usarium verticillioides* and F*usarium graminearum* in imported maize germplasm. Journal of Plant Genetic Resources 20:20-25.

Yu, J., Hennessy, D. A., and Wu, F. 2020. The Impact of Bt Corn on Aflatoxin-Related Insurance Claims in the United States. Scientific Reports 10.

Zhang, X. F., Zou, C. J., Cui, L. N., Li, X., Yang, X. R., and Luo, H. H. 2012. Identification of pathogen causing maize ear rot and inoculation technique

in Southwest China. Southwest China Journal of Agricultural Sciences 25:2078-2082.

Zhang, Y., Zhang, Y., Wang, Z., Wen, J., Han, S., Guo, J., and Xing, Y. 2019. Evaluation of Resistance to Fusarium ear rot in maize inbreds lines. Journal of Plant Genetic Resources DOI:10.13430/j.cnki.jpgr.20180814001.

Zou, C., Cui, L., Zhang, Z., Zhang, X., Li, R., Chen, G., and Li, X. 2017. Evaluation of maize inbred lines for resistance to Fusarium verticilliodes ear rot. Southwest China Journal of Agricultural Sciences 30:1346-1349.

Table 1. Toxigenic species of *Aspergillus* and *Fusarium* associated with maize ear rot by continent (adapted from (Munkvold 2003a)).[a]

Species	Disease symptoms[b]	Africa	Asia	Europe	North/Central America	South America	Oceania
Aspergillus flavus	AER	**X**	**X**	**X**	**X**	**X**	**X**
Aspergillus parasiticus	AER	X	X	X	X	X	X
Fusarium acuminatum	FER, GER		X	X	X	X	
F. asiaticum			**X**				
F. avenaceum	FER, GER		X	X	X		
F. boothii			X				
F. cerealis	GER			X			
F. chlamydosporum	FER, GER		X				
F. crookwellense	GER		X	X			X
F. culmorum	GER		X	**X**	X		X
F. equiseti	FER, GER		X	X	X	X	
F. fujikuroi	FER		X				
F. graminearum	GER	**X**	**X**	**X**	**X**	**X**	**X**
F. meridionale	GER		X				
F. poae	GER			X	X		X
F. proliferatum	FER	X	**X**	**X**	**X**	X	
F. pseudograminearum	GER		X				
F. semitectum	FER		X	X	X		
F. sporotrichioides	GER		X	X	X		
F. subglutinans	FER	X	**X**	**X**	**X**	**X**	X
F. temperatum	FER			X	X	X	
F. verticillioides	FER	**X**	**X**	**X**	**X**	**X**	**X**

[a] X indicates that the species is associated with ear rot; **X** indicates that species is a major cause of ear rot

[b] AER = Aspergillus ear rot, FER = Fusarium ear rot (pink ear rot), GER = Gibberella ear rot (red ear rot)

Figure captions

Figure 1. The most important globally occurring, mycotoxin-producing, ear rot pathogens of maize: 1a, *Aspergillus flavus* usually appears as a powdery olive-green or yellow-green mold scattered across the ear or associated with insect injury; 1b, *Fusarium graminearum* appears as a dense pink to red mold that colonizes the tip of the ear and moves basally, sometime involving the whole ear; 1c, blue-black perithecia of *F. graminearum* may develop on ears, husks, or ear shoots; 1d, *Fusarium verticillioides* symptoms are cottony white to pink, purple, or salmon-colored mold, often associated with insect injury or scattered across the ear; 1e, maize ear showing *F. verticillioides* mold and vivipary symptoms around insect injury; 1f, maize ear showing scattered moldy or "starburst" symptoms, also typical of *F. verticillioides*. In each case, related species can cause similar symptoms.

Figure 2. Cross-functional structure of the MycoKey project. Work Packages (numbered 1 to 10) are organized to work on research, communication, and technology transfer activities across four major crop utilization chains that are the most heavily impacted by mycotoxin contamination.

Figure 3. Summary of MycoKey Maize Working Group Round Table on prioritization of reseach and management efforts for mycotoxins, based on Nominal Group discussion, June, 2018: a, priorities for pre-harvest management of fumonisins; b, priorities for pre-harvest management of aflatoxins; c, priorities for pre-harvest management of deoxynivalenol and zearalenone; d, priorities for post-harvest management of mycotoxins; e, priorities for decontamination/detoxification of mycotoxin-contaminated maize grain; f, priorities for new research and information that will most effectively contribute to improvements in mycotoxin management or reduction in risk.

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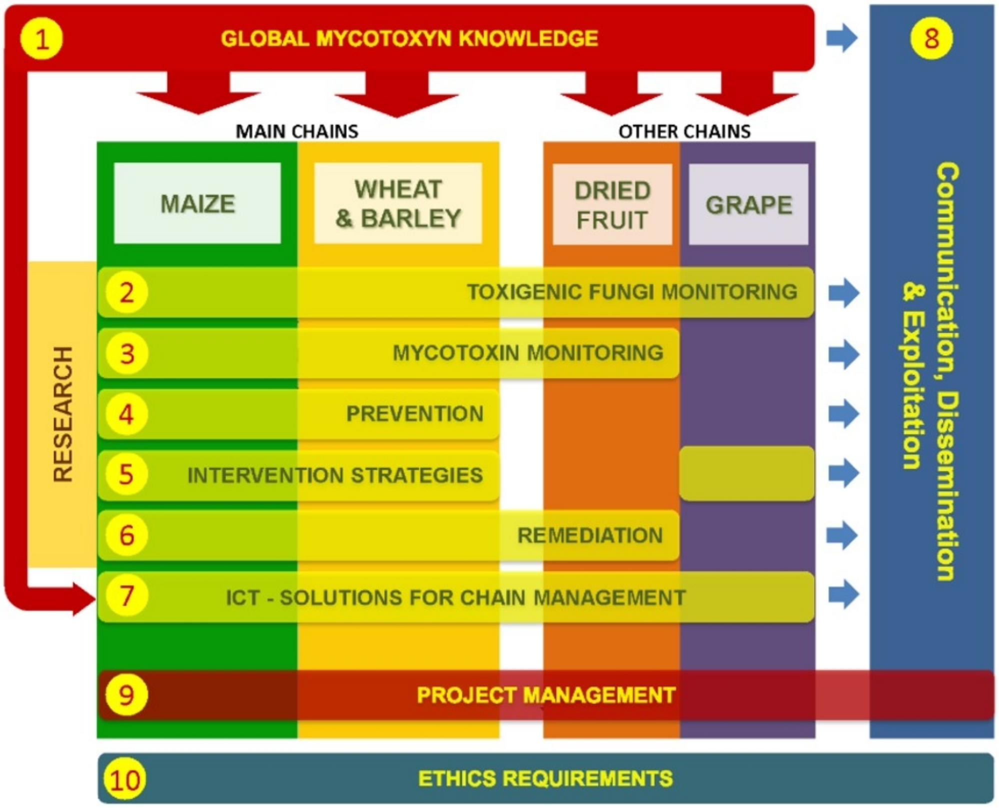

Figure 2. Cross-functional structure of the MycoKey project. Work Packages (numbered 1 to 10) are organized to work on research, communication, and technology transfer activities across four major crop utilization chains that are the most heavily impacted by mycotoxin contamination.

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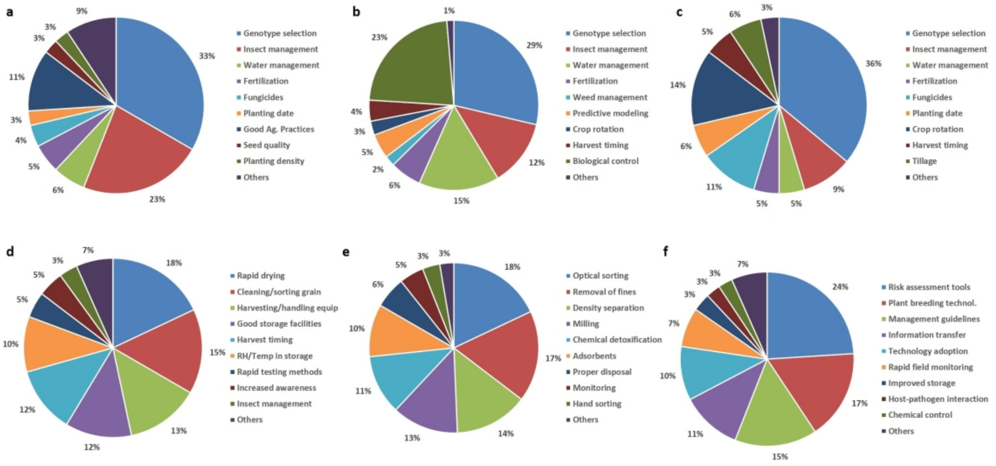

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Supplementary Table 1. Questions posed and responses recorded by MycoKey Maize Working group during its Roundtable Discussion on global maize mycotoxin issues, held in Bucharest, Romania, 6 June, 2018.

What strategies/measures are effective for minimizing fumonisin contamination in maize during crop growth (pre-harvest)?

Rank	Response	Votes
1	**Host resistance/genotype**	**36**
2	**Insect control (ECB)**	**34**
3	**Use of proper hybrids**	**14**
4	**Limited knowledge of good agricultural practices**	**13**
5	Water management	9
6	Fertilization	8
7	Fungicide application	6
8	Seedling density	4
9	Planting time	4
10	Seed quality	4
11	Crop stress management	4
12	Tillage/no tillage	3
13	Forecast	2
14	Prediction model	2
15	Weed management	2
16	Crop rotation	2
17	Crop residues management	2
18	Quality of chemical input	1
19	Incorrect use of input	0
20	Time of harvest	0

Which strategies/measures are effective for minimizing aflatoxin contamination in maize during crop growth (pre-harvest)?

Rank	Response	Votes
1	**Biocontrol**	**34**
2	**Genotype selection**	**32**
3	**Water management/irrigation**	**23**
4	**Insect control (ECB)**	**19**
5	Locally adapted variates	11
6	Fertilization	9
7	Predictive model	7
8	Harvesting time	6
9	Crop rotation	4
10	Weed management	3
11	Planting time	2
12	Seeding density	0
13	Fungicide application	0
14	Intercropping	0
15	Soil management	0

Which strategies/measures are effective for minimizing deoxynivalenol and zearalenone contamination in maize during crop growth (pre-harvest)?

Rank	Response	Votes
1	**Host resistance**	**40**
2	**Crop rotation**	**21**
3	**Fungicide application**	**16**
4	**Insect control**	**14**
5	Locally adapted	10
6	Planting time	9
7	Harvest time	8
8	Fertilization	7
9	Irrigation	7
10	Crop residue management	6
11	Hybrid earliness	4
12	Tillage/no tillage	3
13	Weed control	2
14	Predictive model/risk maps	2
15	Plant density	1
16	Drainage	0
17	Seed dressing	0
18	Seed quality	0

Which strategies/measures are effective for minimizing mycotoxin contamination in maize post-harvest, from harvest through the storage period?

Rank	Response	Votes
1	**Time from harvest to drying /logistic management from harvest to storage**	**23**
2	**Kind of storage**	**18**
3	**Harvest time**	**18**
4	**Differentiate harvesting**	**15**
5	**Cleaning grain**	**15**
6	RH/temperature-moisture control of storage	12
7	Sorting contaminated lots	8
8	Rapid test method	7
9	Increase awareness	7
10	Contamination post-harvest management/separation of contaminated stocks	5
11	Control insect during storage	5
12	Drying methods	4
13	Temperature control during storage	3
14	Harvesting method/prevent mechanical damage	3
15	Checks for relevant mycotoxins	3
16	Grain handling	2
17	Farmer collaboration	2
18	Pre-harvest scouting/satellite imaging	0
19	Monitoring insect during storage	0
20	Methods of transportation	0
21	Chemical treatment post-harvest	0

Which processing steps or decontamination/detoxification actions have impact on mycotoxin content in maize products?

Rank	Response	Votes
1	**Optical sorting**	**27**
2	**Specific weight sorting**	**21**
3	**Fine material removal**	**14**
4	**Sizing grains**	**12**
5	**Sorting after milling**	**10**
6	**Chemical detoxification**	**10**
7	Adsorbents	9
8	Proper methods of disposal	9
9	Monitoring contamination	7
10	Nixtamalization	6
11	Dry milling	6
12	Sorting by hand	5
13	Use of physical adsorbents	3
14	Use of biological adsorbents	3
15	De-hulling grain	3
16	Blending/mixing	3
17	Grain brushing	1
18	Ozone treatment	1
19	Ammoniation	0
20	Control of DDG during bioethanol production	0
21	Aflatoxin degrading microorganisms	0

What information, should be generated or questions answered to facilitate mycotoxin mitigation in the maize chain considering the changing world?

Rank	Response	Votes
1	**New technologies to improve breeding**	**20**
2	**Risk maps of mycotoxin occurrence**	**16**
3	**Standardized georeferenced guidelines**	**13**
4	**Information sharing**	**10**
5	**Hybrid susceptibility list**	**10**
6	**Availability of technologies**	**10**
7	**Tailored management strategies**	**10**
8	Awareness creation	7
9	Develop very rapid diagnostic assays in field	6
10	Robust long term predictions	6
11	Real time monitoring	5
12	Improvement of storage methods for developing countries	5
13	Social aspects of technology adoption	5
14	Improved knowledge on resistance and toxin relationships	5
15	Prevalence data on mycotoxins	4
16	New technologies to improve knowledge on host-pathogen interactions	4
17	Development of new sustainable chemicals	4
18	Options for contaminated commodities	3
19	Improvement of registration process for maize varieties	3
20	Cost benefit analysis of mitigation strategies	2

21	Effects of climate change	1
22	Population dynamics of toxigenic fungi	1
23	Development of new RNAi technologies	0
24	Regulation enforcement	0
25	Effectiveness of actions	0
26	Environmental friendly decontamination methods	0

MycoKey Maize Working Group Round Table discussion session participants. Front row (L to R): George Mahuku, Antonio Logrieco, Paola Battilani, Alejandro Ortega-Beltran. Back row (L to R): Marco Camardo Leggieri, Oana Dumitru (IBA Bucharest), Alessandra Lanubile, Roberta Palumbo, Gary Munkvold, Adriana Torres, Akos Mesterhazy, Irina Smeu, Geert Haesaert, Nastasia Belc (IBA Bucharest)

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