CSIRO PUBLISHING

Australian Journal of Experimental Agriculture, 2008, **48**, 358–366 www.publish.csiro.au/journals/ajea

Modelling climatic risks of aflatoxin contamination in maize

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Abstract. Aflatoxins are highly carcinogenic mycotoxins produced by two fungi, *Aspergillus flavus* and *A. parasiticus*, under specific moisture and temperature conditions before harvest and/or during storage of a wide range of crops including maize. Modelling of interactions between host plant and environment during the season can enable quantification of preharvest aflatoxin risk and its potential management. A model was developed to quantify climatic risks of aflatoxin contamination in maize using principles previously used for peanuts. The model outputs an aflatoxin risk index in response to seasonal temperature and soil moisture during the maize grain filling period using the APSIM's maize module. The model performed well in simulating climatic risk of aflatoxin contamination in maize as indicated by a significant R^2 ($P \leq 0.01$) between aflatoxin risk index and the measured aflatoxin B1 in crop samples, which was 0.69 for a range of rainfed Australian locations and 0.62 when irrigated locations were also included in the analysis. The model was further applied to determine probabilities of exceeding a given aflatoxin risk in four non-irrigated maize growing locations of Queensland using 106 years of historical climatic data. Locations with both dry and hot climates had a much higher probability of higher aflatoxin risk compared with locations having either dry or hot conditions alone. Scenario analysis suggested that under non-irrigated conditions the risk of aflatoxin contamination could be minimised by adjusting sowing time or selecting an appropriate hybrid to better match the grain filling period to coincide with lower temperature and water stress conditions.

Additional keywords: *Zea mays* L.

Introduction

Maize (*Zea mays* L.) is a major source of human food and animal feed. However, it is also a favourable host for two fungi, *Aspergillus flavus* and *A. parasiticus*, which produce aflatoxins, of which aflatoxin B1 is the most toxic and carcinogenic. For this reason, there are worldwide regulations that limit levels of aflatoxin B1 and other mycotoxins in food and feeds being traded. In Australia, aflatoxins are regulated in grain for human food to 'as low as is reasonably achievable', and in maize used in livestock feed, aflatoxin B1 is limited to 20 µg/kg. The National Agricultural Commodities Marketing Association (NACMA) uses trading standards for total aflatoxins (B1 + B2 + G1 + G2) in maize of 5 µg/kg for milling grade, 15 µg/kg for prime grade, 20 µg/kg for feed #1, and 80 µg/kg for feed #2 (NACMA 2003).

Economic losses associated with mycotoxins, including aflatoxins, to the maize industry in the United States (US) are by and large associated with regulatory losses (Robens and Cardwell 2005) and this is also the general situation present in Australia. The cost of meeting the industry standards for human food of 5 µg/kg can be high, especially during years when contamination in the crop is high. In Australia, the main challenge to reduce these costs is by detecting and limiting risks of aflatoxin contamination during the preharvest stage, as dry conditions prevail during final maturation and harvest in most growing regions, and storage and processing technologies are generally adequate to limit significant postharvest contamination (Webley and Jackson 1998). Although the Australian maize industry is relatively small, it is still a significant contributor to the economy of some regional areas in Queensland (Qld) and New South Wales (NSW) (www.abs.gov.au/Ausstats, accessed 12 December 2007). Very limited research work has been conducted in Australia to understand the extent of preharvest aflatoxin contamination in maize apart from limited field surveys, which found that aflatoxin was a relatively minor problem (Blaney 1981; Blaney *et al*. 1984, 1986). Some recent episodes of high preharvest aflatoxin contamination in Australian maize have, however, highlighted a need to revisit the aflatoxin contamination problem more thoroughly (Blaney *et al*. 2008).

An appreciable amount of work on aflatoxins in maize has been conducted elsewhere (Abbas 2005). It has been clearly shown that preharvest infection by *A. flavus* and subsequent aflatoxin production in maize depends primarily upon climatic conditions (Munkvold 2003). Generally, plant stress factors such as high temperature and drought favour colonisation and toxin production by *Aspergillus* species (Moreno and Kang 1999) and their effects are exacerbated by insect damage (Dowd *et al*. 2005). The development of a model to simulate the risk of aflatoxin contamination could be helpful in the identification and characterisation of environments favourable for aflatoxin production and ultimately to assist in the preharvest management of aflatoxin. Notwithstanding the better understanding of the causal factors involved in aflatoxin

 10.1071/EA06101 0816-1089/08/30358

production in maize, there have only been very limited attempts towards the development of models to predict the risk of preharvest aflatoxin contamination in this crop. A complex mathematical model that integrates the effects of temperature, water activity, pH and colony size on mould growth and aflatoxin production under laboratory conditions was proposed (Pitt 1993); however, the approach has not been validated under field conditions. Dowd (2002) more recently reported a model to predict aflatoxin production in maize for the US Corn Belt, but due to a lack of detailed proprietary information in public domain it has had limited application outside of the US.

A model to predict the risk of aflatoxin contamination has been developed for peanuts in Australia (Wright and Hansen 1997; Wright *et al*. 2003, 2005). This model quantifies risk of aflatoxin contamination at a given location in response to the combined effects of plant-available soil water and soil temperature in a daily time step commencing from the late pod filling stage. The model computes an aflatoxin risk index (ARI) as a percentage, with 0 as nil and 100 as severe risk of aflatoxin contamination. In peanuts, a positive correlation between the ARI and actual amount of aflatoxin measured is generally observed, although other factors such as insect damage have also been found to significantly affect this relationship (Rachaputi *et al*. 2004). Nevertheless, the use of an ARI approach in peanuts has provided a sound basis for assessing in-season aflatoxin risk associated with climatic conditions and is currently being used by growers to determine harvesting time in order to minimise aflatoxin contamination (Wright *et al*. 2005). The development of a maize aflatoxin simulation model similar to the one developed for peanut could allow assessment of the in-season aflatoxin risk based on current seasonal conditions, as well as the assessment of longer term risk using historical climatic data. This paper describes the development of a simulation model to predict the risk of aflatoxin contamination in maize and its application to examine the potential for aflatoxin contamination in different environments and in response to changes in cultural practices.

Materials and methods

Maize aflatoxin model

The maize aflatoxin model was developed as a subcomponent of the APSIM maize module, which uses ambient temperature, radiation, rainfall, soil water and soil nitrogen to simulate maize growth and yield on an area basis on a daily time step (Keating *et al*. 2003). The model is based on similar principles to those used to quantify climatic risk of aflatoxin contamination in peanuts (Wright *et al*. 2003). In conjunction with the APSIM-maize module, the model identifies the coincidences of <20% fractional available soil water and ambient air temperature between ≥22 and ≤35°C from the start of the grain filling stage, which are accumulated in an aflatoxin risk index calculator. The temperature and soil water parameters used were derived from previous laboratory studies with peanuts. The model assumes inoculum of aflatoxigenic fungi are always present in the soil, which is a reasonable assumption given that the temperature range favourable for the growth of maize also favours germination and growth of *A. flavus* (Marín *et al*. 1998).

Validation of maize aflatoxin model

To validate the model we used results from previous surveys, where aflatoxin B1 analysis was conducted on 805 samples collected from truckloads of maize delivered by 107 growers to a depot in the Burnett district in the 1977–78 season (Blaney 1981), 293 samples from the truckloads delivered by 111 growers to the Atherton Marketing Board in the 1981–82 season (Blaney *et al*. 1984), and 174 samples received directly from 80 growers in the 1982–83 season (Blaney *et al*. 1986). In 2005, 184 samples, including both rainfed and irrigated maize from several Qld and NSW locations, were analysed for aflatoxin B1 (Blaney *et al*. 2008).

To quantify the risk of aflatoxin contamination, the model was run for the survey years for all locations surveyed in 1978, and at least one location from each district surveyed in 1982 and 1983 for a range of monthly sowings usually followed in these regions, as precise cultural details for these crops were not available. All locations surveyed in 1982 and 1983 were from the Atherton Tablelands of Far North Qld, with only a few samples testing positive for aflatoxin. We also ran the model to quantify aflatoxin risk for rainfed and irrigated locations which had positive aflatoxin samples analysed from the 2005 season. For the 2005 simulation, the actual dates of sowing (Table 2) and other cultural practices followed were used to simulate the ARI. For all locations surveyed before 2005, it was assumed that maize was grown on soils which had ~140 mm plant available water holding capacity, and with one third of the profile from the top being full at the start of the season. Genetic parameters for the Pioneer hybrid 3527 were used. Weather data for each of the locations was accessed from the 'SILO' weather site (www.nrm.qld.gov.au/silo, accessed 12 December 2007). In 2005, soil depth, starting water, rainfall and irrigation details provided by surveyed growers were used to run the model.

To establish the relationship between ARI and aflatoxin content in the samples, the maximum value of ARI was regressed with the maximum value of aflatoxin B1 for the respective locations, assuming the maximum contamination occurred in the crop that had experienced the most favourable conditions for aflatoxin production. This relationship was established for rainfed locations, as well as for combined rainfed and irrigated locations.

Probability analysis of long-term aflatoxin risk in Qld's maize production regions

The APSIM maize model incorporating the aflatoxin module was run using 106 years of weather data for the Burnett district (Kingaroy and Gayndah), central Qld (Emerald) and north Qld (Atherton Tableland) regions to determine the long-term risk of aflatoxin contamination in these regions. For all the locations, it was assumed that maize was grown on soils with ~140 mm plant available water holding capacity and the genetic parameters of Pioneer hybrid 3527 were used. The APSIM output was converted into a Microsoft Access database using the APSIM Outlook Manager, which was then used to develop probability distributions using the APSIM Outlook program. This software is part of the APSIM software package (Keating *et al*. 2003). The probability distributions gave a likelihood of the random variable (e.g. ARI) shown on the horizontal axis exceeding a given value. Long-term averages of rainfall, mean temperature and stress index for different sowings for these locations were calculated using a Microsoft Excel pivot table. The stress index is a water deficit factor computed by APSIM and its 0 value represents complete stress and 1 represents nil stress.

Effect of cultural practices to minimise aflatoxin risk in maize

The effects of two hybrids differing in maturity by 3–4 weeks, sowing time, and plant population were simulated using 106 years of daily weather records for Gayndah, as this environment was found to be generally more conducive to aflatoxin production than Kingaroy and Kairi. The outputs from these simulations were also converted into a Microsoft Access database, which was used for plotting probability distributions using the APSIM Outlook program, as described above.

Results

Model validation

The maximum ARI simulated for the 15 October–15 January sowings in the 1978 season in the Burnett district was 33% for the Cloyna–Murgon–Tansey–Goomeri region, which was reported to have a maximum aflatoxin B1 content of 150 μg/kg maize (Table 1). The Gayndah location had a similar ARI as Cloyna followed by Wondai-Proston. The north Qld locations surveyed were free from aflatoxin in 1982 and the model simulated a nil value of ARI for these locations for sowings conducted between 15 December and 15 January, which are generally practised in the region. For locations surveyed in 1983 (a drier season than 1982), varying values of ARI occurred, which was highest for the Mareeba location. Mareeba also had the highest aflatoxin contamination recorded in the survey. There were some locations, such as Atherton, Kairi, Malanda, and Tolga, which were free from aflatoxin, with a corresponding low value of ARI being simulated. The overall percentage of aflatoxin positive samples reported in these surveys comprising of 1272 samples was 1.6%.

In 2005, the simulated ARI was highest for Gayndah followed by that for Narromine. A total of 184 samples were collected from both rainfed and irrigated locations in this season; 22% of these were aflatoxin positive (Table 2). About 5% of these samples exceeded 15 μg aflatoxin B1/kg maize. A majority of these samples came from three sites, Wooroolin and Gayndah in Qld and Narromine in NSW. Rainfed maize crops throughout the Burnett district suffered from significant drought during this season; however, there were substantial differences in ARI among locations representing different regions. The samples from Gayndah were particularly high in aflatoxin, with the model accumulating a high ARI for this location compared with those from the nearby south Burnett locations in Kumbia, Kingaroy and Wooroolin. The ARI for Kairi in north Qld was <1 and the samples from this location did not contain aflatoxin B1.

The relationship between the maximum ARI and the maximum aflatoxin contamination detected in different samples was significant (R^2 = 0.69, P < 0.01, n = 25) for rainfed locations (Fig. 1). The inclusion of two irrigated locations from NSW in this relationship reduced the coefficient of variation

Table 1. Percentage of aflatoxin positive samples and maximum aflatoxin B1 content detected in 1379 samples of rainfed maize collected from different Queensland locations during 1978, 1982 and 1983 and simulated aflatoxin risk index (ARI)

Location	Sowing time	Survey results Positive samples (%)	Survey results Maximum aflatoxin B1(μg/kg)	Range of simulated ARI (%)
1978 survey data (Blaney 1981)				
Gayndah	15 Oct.–15 Jan.	4	50	3–34
Kumbia	15 Oct.–15 Jan.	1.3	20	0–6
Cloyna	15 Oct.–15 Jan.	4.5	150	0–33
Proston	15 Oct.–15 Jan.	1.5	25	0–20
Wooroolin	15 Oct.–15 Jan.	1.5	15	0–5
1982 survey data (Blaney et al. 1984)				
Atherton	15 Dec.–15 Jan.	0	0	0
Herberton	15 Dec.–15 Jan.	0	0	0
Lakeland	15 Dec.–15 Jan.	0	0	0
Malanda	15 Dec.–15 Jan.	0	0	0
Kairi	15 Dec.–15 Jan.	0	0	0
Walkamin	15 Dec.–15 Jan.	0	0	0
1983 survey data (Blaney et al. 1986)				
Atherton	15 Dec.–15 Jan.	0	0	0–4
Herberton	15 Dec.–15 Jan.	0	0	0
Malanda	15 Dec.–15 Jan.	0	0	0–7
Lakeland	15 Dec.–15 Jan.	0	0	0
Kairi	15 Dec.–15 Jan.	0	0	0–8
Mareeba	15 Dec.–15 Jan.	20	40	0–23
Tolga	15 Dec.–15 Jan.	5	1	0–3
Walkamin	15 Dec.–15 Jan.	0	0	0

Table 2. Range of observed aflatoxin contamination in maize samples compared with the aflatoxin risk index, sowing date, plant density and irrigation in seven locations in Queensland (Qld) and New South Wales (NSW) in 2005

Location	Irrigated	Date of sowing	Plant density (no. of plants/m^2)	Total no. of samples	No. of positive samples	Aflatoxin B1 (μg/kg)	Risk index
Darlington Point, NSW	Yes	16 Oct.04	6.0	3	1	0–5	0
Narromine, NSW	Yes	24 Dec. 04	10.0	10	4	0–80	9.2
Kumbia, Qld	No	2 Jan. 05	2.5	9	5	0–3	0.5
Kingaroy, Qld	No	15 Dec. 04	2.5	36	7	0–7	0.2
Wooroolin, Qld	No	15 Dec. 04	2.5	18	10	0–20	4.5
Gayndah, Qld	No	3 Jan. 05	2.5	10	9	0–53	21.9
Kairi, Qld	No	5 Jan. 05	2.5	2	0	0	0.4

(R^2 = 0.62, P < 0.01, n = 27), although the slope of the relationship remained unchanged (Fig. 1).

Comparative risk of aflatoxin contamination in Qld's regions

Fig. 2 shows the long-term probability of exceeding various ARI for different planting dates at the 4 locations, which represented some of the major maize growing regions in Qld. For example, the probability of exceeding an ARI of 50% for 15 December sowings at Emerald was ~50%. Among the four locations, the long-term probability of ARI exceeding a given value was greatest for Emerald, followed by Gayndah, Kingaroy and Kairi regions for each of the sowing dates between 15 October and 15 January (Fig. 2). Fig. 2 also shows that sowing time influenced ARI across all regions, with the 15 October sowing time generally producing the highest values, and 15 January sowing time producing the lowest values across all locations.

The climatic differences and stresses during the reproductive phase of the crop between locations that underlie these differences in aflatoxin risk are shown in Fig. 3. On long-term averages, Kairi has appreciably more rainfall and hence less water stress during the grain filling period compared with other locations. Kingaroy has similar rainfall to Emerald and Gayndah, but cooler temperatures during the grain filling period. Emerald and Gayndah both have higher temperatures and lower rainfall resulting in a high degree of water stress experienced by the crop.

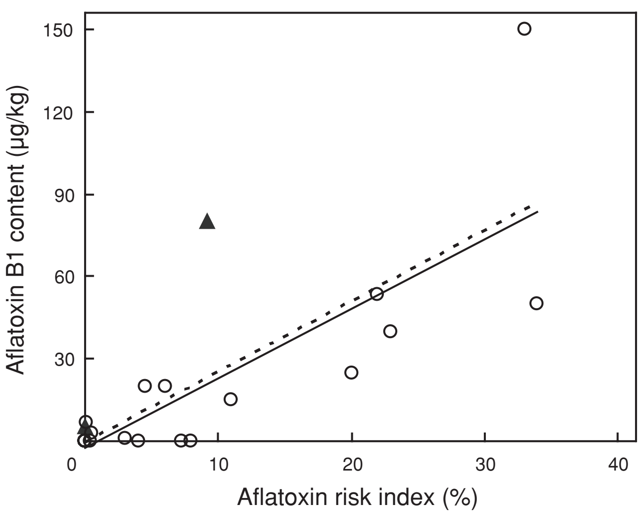

Fig. 1. Relationship between measured aflatoxin B1 and the simulated aflatoxin risk index (ARI) for rainfed (○) and irrigated (▲) maize grown in Queensland and New South Wales. The linear regressions for only rainfed locations are shown with solid line and all locations with dashed line. The regression equations for only rainfed locations was $y = 2.5339 \times \mathrm{ARI} - 2.57$ and for all locations $y = 2.5636 \times \mathrm{ARI} - 0.2886$. The regressions were significant at the $P = 0.01$ probability level.

Scenario analysis of the effect of quick and slow maturating hybrids and plant density on aflatoxin risk

Fig. 4 shows that a long duration maize hybrid was simulated to have a much higher probability of exceeding a given ARI for an early sowing at Gayndah compared with an early-maturing hybrid, while the opposite was true for later sowings. For example, for a quick hybrid with an early sowing, there was a 45% probability of exceeding an ARI of 50%, which to extrapolate from the data in Table 2, could indicate extensive contamination. However, there was only a 40% chance of exceeding an ARI of 10% for a slow hybrid in a late sowing.

Fig. 5 shows that for an early sowing of a quick hybrid at Gayndah, use of a higher plant density (10 plants/m^2) simulated a much greater probability of exceeding a given value of ARI than at a lower density of 2.5 plants/m^2. For example, reducing plant density from 10 to 2.5 plants/m^2 reduced the probability of exceeding an ARI of 50% from 40% to 10%. However, greater grain yield could be realised at the higher plant population in ~60% of the years (when rainfall was higher).

Discussion

Observed aflatoxin contamination and its prediction by the model

As many as 22% of the maize samples analysed for aflatoxin in 2005 tested positive for aflatoxin whereas in earlier surveys (Blaney 1981; Blaney *et al*. 1984, 1986) less than 2% of samples were positive. Around 5% of these samples exceeded the 20 μg/kg limit in Qld regulations for stock feed for dairy cattle (Blaney *et al*. 2006). This result is consistent with the observation that the risk of aflatoxin contamination for maize grown in Australia has increased in recent years (Blaney *et al*. 2008), which has been associated with persistent dry conditions and increases in ambient temperature. This observation also further reinforces the view that more concerted effort is needed to tackle this problem (Blaney *et al*. 2008).

The detection of aflatoxin in rainfed crops grown in the Burnett district in earlier surveys, as well as in 2005 (Blaney

1981; Blaney *et al*. 2008) was not unexpected, as this region frequently experiences drought as well as high temperature during the grain filling stage of maize, both of which are known to favour aflatoxin production (Moreno and Kang 1999; Munkvold 2003). The model was able to discern more favourable Burnett locations from less favourable Burnett locations, where temperatures are milder and droughts are less severe and frequent (based on long-term climatic averages). The ARI accounted for up to 69% of the observed variation in aflatoxin B1 content for rainfed locations suggesting that the quantification of climatic risk for aflatoxin contamination using the ARI-based approach was reasonably accurate. The relationship between ARI and aflatoxin contamination shown in Fig. 1 suggests that at 100% ARI there is a strong likelihood of encountering maize crops containing >250 µg aflatoxins/kg of maize, but the extrapolation might not hold at these levels or be confounded by crop failure before harvest.

The model could generally simulate an ARI of >0 for all the positive samples of rainfed locations, albeit with a low value in some cases. This suggests the model could be a useful tool for in-season monitoring and could indicate whether or not the harvested maize samples should be tested for aflatoxin contamination. If the ARI exceeds 8% then there is a chance of detecting aflatoxin that exceeds the stockfeed requirement, and testing is recommended.

There were a few locations in the Atherton Tableland region surveyed in 1983 in which ARI was >0, but no aflatoxin was detected. It is possible that such locations may have actually received more rainfall than that measured at the nearest climatic station, which was used as an input into the model, thus resulting in a false value of ARI. In view of the large spatial and temporal variability in rainfall that is generally observed within a location, it is preferable to use the rainfall measured within the paddock where the crop has been actually grown.

The model simulated little risk of aflatoxin contamination (i.e. ARI = 0) for Darlington Point in NSW in 2005, although some aflatoxin contamination was detected (Table 2). Similarly for Narromine, measured aflatoxin was much more than was expected on the basis of model simulation. The detection of aflatoxin in samples from these irrigated NSW locations was unexpected, as aflatoxins are seldom found in fully irrigated maize (Cole *et al*. 1982), unless it is attacked by insects (Windham *et al*. 1999). A major role of irrigation in preventing aflatoxin contamination is in the maintenance of high water status in the kernel, thus preventing infection and aflatoxin production by *A. flavus*, possibly through phytoalexin formation. At Narromine, where maize samples with maximum aflatoxin B1 concentrations of 80 µg/kg were observed, it appears that these crops were not adequately irrigated, thus resulting in aflatoxin production. It has been recognised for many years that inadequate or uneven irrigation, often associated with varying soil depths, is a primary factor in occasional aflatoxin contamination in the Murrumbidgee Irrigation Area (B. Blaney, pers. comm.). Bruns and Abbas (2005*a*) also attributed a high aflatoxin concentration (~561 µg/kg) to inadequate irrigation accompanied by high

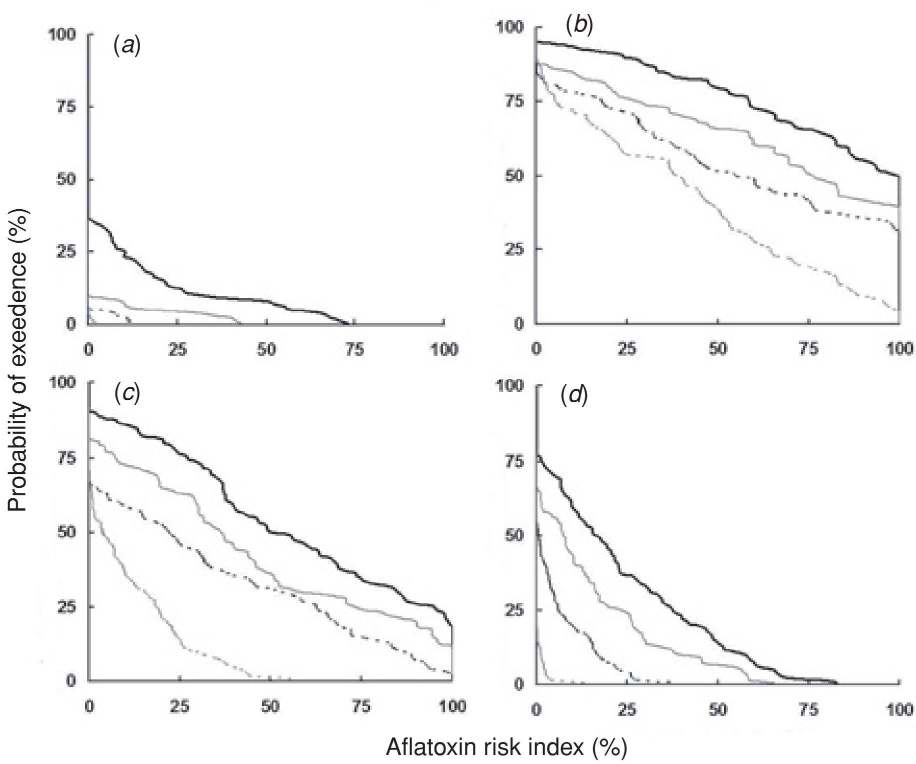

Fig. 2. Long-term probability of exceeding a given aflatoxin risk index (%) at 15 Oct. (solid black line), 15 Nov. (solid grey line), 15 Dec. (dashed black line), and 15 Jan. (dashed grey line) sowings at (*a*) Kairi, (*b*) Emerald, (*c*) Gayndah and (*d*) Kingaroy in Queensland.

temperature (>35°C) during the grain filling period in a maize trial conducted in the US, in which yields as high as 10.3 t/ha were recorded. Maximum temperatures of ~34°C have also been reported to prolong the grain filling period of maize kernels and moderately constrain seed storage processes by affecting starch metabolism enzymes (Wilhelm *et al*. 1999), which could also make them vulnerable to *A. flavus* invasion and aflatoxin production.

Even when the water stress and temperature effects experienced by the crop at Narromine during the 2005 season were accounted for by the model, there was appreciable under-simulation of the ARI, which on the basis of regression equation given in Fig. 1 should have amounted to a value of ~30 (Table 2). The crop at this location, in addition to being inadequately irrigated, was also moderately attacked by insects (not quantified). As stated above, insect attack can exacerbate *A. flavus* infection and aflatoxin production even under well irrigated conditions, provided temperatures are favourable for aflatoxin production (Windham *et al*. 1999). Since temperature has an overriding influence on aflatoxin production, a crop attacked by insects, however, may not always have aflatoxin contamination (Widstorm *et al*. 1990). Blaney *et al*. (1986) reported that in spite of severe *Helicoverpa* damage in Far North Qld only one out of the 174 samples had aflatoxin contents that exceeded the Qld stock food standard. Two other samples had much lower concentrations, which were associated with only moderate aflatoxin risk, as per the model simulations. No information on the extent of insect damage was available for samples from Darlington Point. There was also appreciable under-simulation of ARI for the Cloyna–Murgon–Tansey–Goomeri region (Table 1). The reasons for this result are not clear, but could be due to factors such as insect attack or rainfall being less than that recorded at the nearest meteorological station, for which no information was available. For these reasons inclusion of data from the irrigated locations in the regression equation reduced the R^2 values from 0.69 for rainfed locations to 0.62 where all locations were included. At present, the maize aflatoxin model only quantifies the climatic risk of aflatoxin contamination and does not have the capability to account for contributions that insect damage may contribute to this risk.

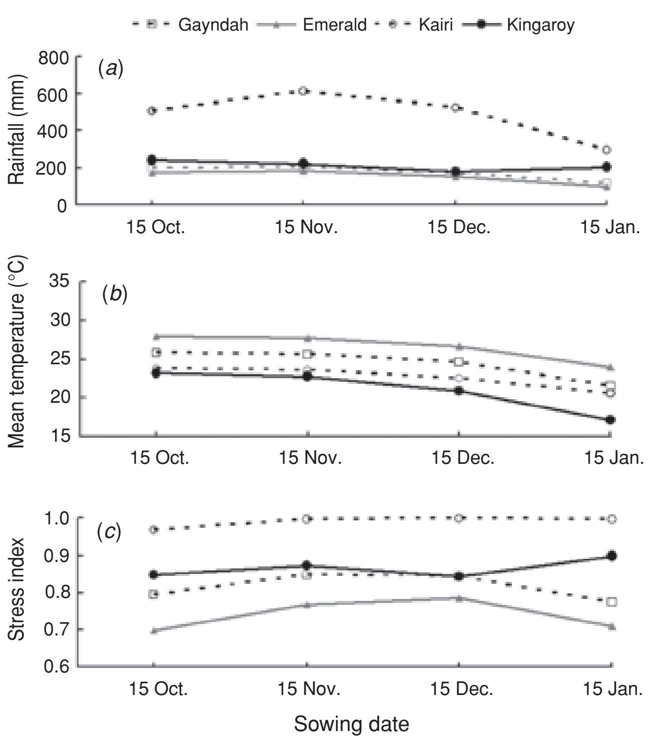

Fig. 3. (*a*) Long-term average rainfall and (*b*) ambient temperature during the reproductive stage and (*c*) stress index during the last 60 days of crop growth at Gayndah, Emerald, Kairi and Kingaroy in Queensland.

Comparative risk of aflatoxin contamination in Qld regions

Analysis of maize samples received from the rainfed maize growing regions suggested that the proportion of aflatoxin contaminated samples was only high (in regard to suitability for stock other than ruminants) in some locations in the Burnett district. Further scenario analysis of aflatoxin risk also suggested that the probability of higher ARI was greater in the north Burnett around Gayndah, as well as in central Qld districts. The differences observed in ARI among locations and sowing dates can be further explained by analysing the temperature conditions and degree of crop water stress experienced by maize in these regions (Fig. 3). At Kairi, the lower probability of high ARI was mainly due to the higher and more reliable rainfall experienced during the grain filling period, while at Kingaroy it was more closely associated with lower temperature conditions. In contrast, at Gayndah and Emerald the greater probability of high ARI was largely related to both higher temperatures and severe drought conditions during the grain filling period. The high incidence of aflatoxin positive samples in Gayndah in 2005 and the absence at Kairi is consistent with this analysis. Similarly, in surveys conducted in

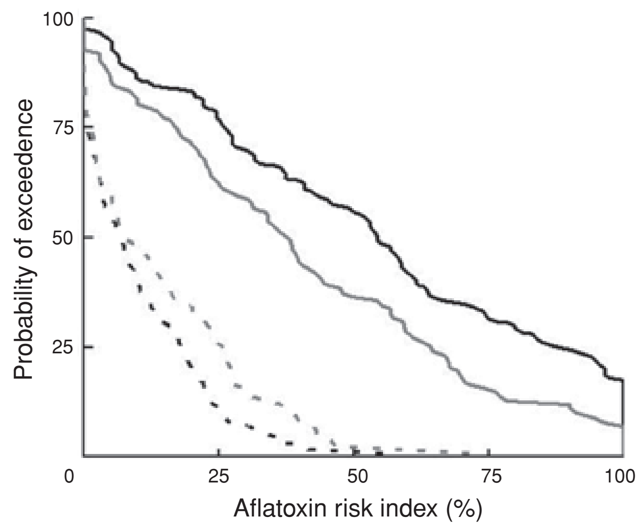

Fig. 4. Long-term probability of exceeding a given aflatoxin risk index in simulated sowings at Gayndah for a slow hybrid under an early sowing (solid black line), for a slow hybrid under a late sowing (dashed black line), for a quick hybrid under an early sowing (solid grey line) and for a quick hybrid under a late sowing (dashed grey line).

the Atherton Tableland region near Kairi, Blaney *et al*. (1984, 1986) found that aflatoxin was only a minor problem in maize. A similar observation of regional differences in aflatoxin risk in the Burnett region and the Atherton Tableland has been made in peanuts (Wright and Hansen 1997). The environmental limits for crop production as well as aflatoxigenic potential of *A. flavus* seem similar in maize and peanuts (Abbas *et al*. 2005), although aflatoxin contamination in peanuts is largely related to variation in soil temperature rather than ambient temperature due to the subterranean growth habit of pods. The main difference between these crops is in the computation of ARI, where the aflatoxin risk in maize is driven by ambient air temperature, compared with soil temperature for peanut.

The other maize growing areas of Qld not covered in this study are in the Darling Downs where some irrigation is used and in the Southern Downs, which are mostly rainfed. Similarly, the other important rainfed maize growing areas lie in the northern rivers and tablelands in NSW. The soils in the Qld regions, in addition to being irrigated in some cases, hold much more water, and in NSW crops receive more rainfall than in the Burnett region. Therefore, the degree of drought stress experienced in these locations is likely to be less. However, these crops could still be vulnerable to aflatoxin risk should dry conditions occur as ambient temperatures could still be favourable for aflatoxin production depending upon when sowings are conducted.

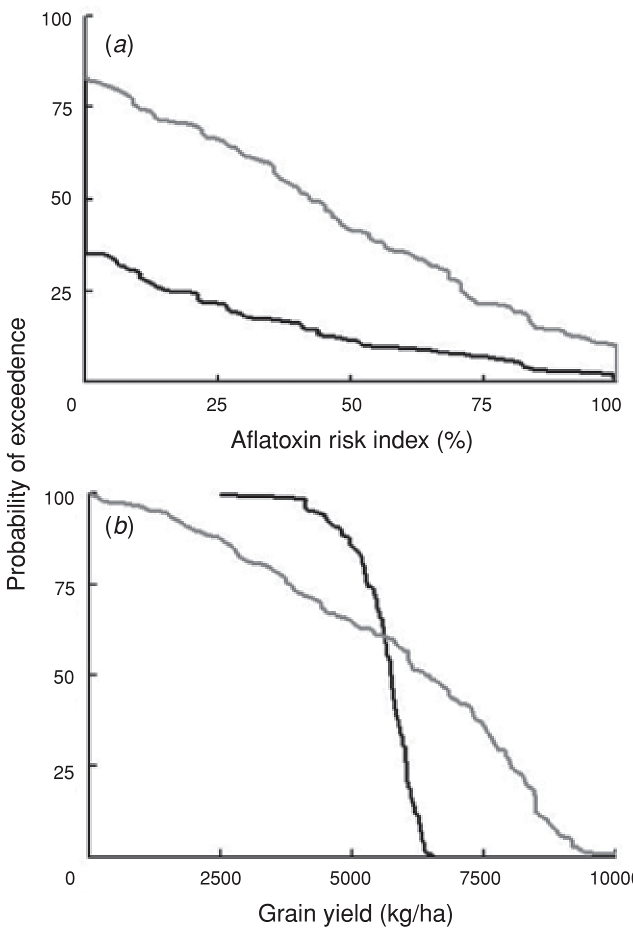

Fig. 5. (*a*) Long-term probability of exceeding a given aflatoxin risk index and (*b*) grain yield in simulated sowings at Gayndah, Queensland on 15 October under 2.5 plants/m^2 (black line) and 10 plants/m^2 (grey line) density.

Options for minimising aflatoxin risk in maize derived from the aflatoxin model analyses

Growers often have to make decisions about what type of hybrid will be suitable for their region and what is the optimal sowing date. Scenarios examined in this study suggest that these decisions could have a profound impact on potential aflatoxin contamination, which may also affect their gross margins. The probability distributions suggested that in the Burnett district, a late-maturing hybrid was more likely to have significantly higher ARI than an early-maturing hybrid during the early planting window (October–November), whereas the opposite was true for the late planting window (December–January). An early-maturing hybrid although having lower yield potential, can escape from terminal drought for the early sowing dates thus resulting in a lower probability of exceeding a given ARI. However, for later sowings, an early-maturing hybrid may be exposed to higher temperatures during maturation compared with a late-maturing hybrid.

Similarly, plant population could be one of the critical agronomic factors involved in managing aflatoxin, as it will impact on the rate and degree of stress development. Probability distributions given in Fig. 5 suggest that in more favourable years when the probability of exceeding a given ARI would be only 25% or less, yield obtained at 10 plants/m^2 could be more than 8 t/ha compared with a maximum of 6 t/ha or less being realised at 2.5 plants/m^2. Likewise in drought years when the probability of exceeding a given ARI would be ~80%, yield of the crop grown at 10 plants/m^2 could be only up to ~3.5 t/ha compared with 5.5 t/ha at 2.5 plants/m^2. Our analysis suggests that in such rainfed environments, while greater yields could be realised at higher plant populations in a majority of years, this management strategy may also result in a higher risk of aflatoxin contamination. For this reason, in such high risk regions and sowing times it may be safer to use a more conservative plant population. It is anticipated that with improvements in climate forecasting methods, it will be possible to take greater advantage of such scenario analysis in maximising yields and minimising aflatoxin risk under rainfed conditions. Under irrigated conditions no such benefit may be apparent as Bruns and Abbas (2005*b*) found no association between plant population and aflatoxin contaminations in the US.

Therefore, the model can be used to make key pre-season decisions on various agronomic options that can reduce the risk of aflatoxin contamination, as well as maintaining high yield levels. In addition, the model can assist with in-season monitoring to determine when the conditions for high aflatoxin risk have commenced, using a similar approach to that used in the AFLOMAN decision support program in peanuts (Wright *et al*. 2005; http://www.apsim.info/apsim/afloman/, accessed 12 December 2007). If limited irrigation is available, the model could give valuable information to growers on the judicious use of irrigation to prevent a rise in ARI to mitigate the risk of aflatoxin accumulation.

Summary and conclusions

The initial validation studies have suggested that the maize aflatoxin model is able to successfully predict the risk of aflatoxin contamination with a reasonable level of accuracy, especially for rainfed situations. The model was able to quantify regional differences in risk, which could be of some assistance for the maize processing industry to segregate produce from high and low risk fields or regions. One of the major limitations identified in the present model is the inability to account for the incidence of insect damage in the computation of ARI. Further experimentation and model development in relation to this aspect would increase model versatility for aflatoxin management in maize. Scenarios of a range of agronomic factors that could impact on aflatoxin risk in maize are presented which suggest the model could be used to make pre-season decisions to lower the impact of climatic factors involved in increasing contamination in the crop. Generally, agronomic factors that reduce the severity of drought or exposure of the crop to high temperature during the grain filling will reduce the risk of aflatoxin contamination. Maize cultivation in areas with low ARI should be encouraged to take advantage of the full season, whereas in environments or seasons where ARI is high, either supplementary irrigation or appropriate management practices to minimise risk of drought should be actively recommended. Finally, the model needs to be more rigorously validated against controlled experimental data before it can be more widely adopted by the industry.

Acknowledgements

The authors are thankful to Barry Blaney and Lisa Bricknell for providing data for validating the model. We thank the Grains Research and Development Corporation for funding support to conduct this study.

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Manuscript received 15 March 2006, accepted 29 June 2007