The climate-induced alteration of future geographic distribution of aflatoxin in peanut crops and its adaptation options

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Abstract

Because of its negative effect on health, aflatoxin has become one of the most important mycotoxins in the world. As climate stress is one of the main triggers of aflatoxin incidence, climate change could affect its geographic distribution. The primary aim of this study was to examine the effect of climate change on the future distribution of aflatoxin in peanut (*Arachis hypogaea* L) crops in Australia. The projected distributions in 2030, 2050, 2070, and 2100 were modelled by employing CLIMEX (CLIMatic indEX) model using two Global Climate Models (GCMs), i.e. CSIRO-Mk3.0 and MIROC-H based on SRES A2 and SRES A1B climate scenarios. This study has successfully developed CLIMEX model parameters for aflatoxin, and confirmed the climatic zones preference of aflatoxin incidence, as concluded by other studies. Therefore, the model parameters are applicable in all parts of the world. The projection results in Australia confirm that climate change affects the future distribution of aflatoxin, including the distribution in the current peanut growing areas. Shifts in aflatoxin invasion areas from the tropical and subtropical climate zones of the eastern part of Australia to the temperate climate zones of the south-eastern and south-western parts of the country were projected by 2100. Thus, adaptation and mitigation measures are needed to overcome the negative impacts in the future. Options for these measures include relocation of planting areas, development of host-plant resistance, proper agricultural practices, and mitigation actions by using physical, chemical, and biological approaches.

Keywords: CLIMEX, aflatoxin, climate change, Australia, mitigation, adaptation

1. Introduction

The agriculture sector depends on a stable and predictable climate, so it is vulnerable to climate change. Changes in mean temperature, frequency of climate variability, and occurrence of extreme weather events, such as drought, very high or very low temperatures, heavy rain, and floods (Gornall et al. 2010) may affect agricultural systems, including plant disease epidemiology, severity, and geographical distribution (Chakraborty et al. 2000; Luck et al. 2011). Specifically, the reproduction, distribution, and severity of plant pathogens may be affected by a changing climate (Gautam et al. 2013). A latitude bias in the range shifts of crop pests and pathogens indicates the impact of global warming (Bebber 2015). For example, a recent study shows the geographical expansion of the incidence of aflatoxin-producing fungi and aflatoxin in temperate climate regions, which have not previously experienced these phenomena (Baranyi et al. 2015). Therefore, there is a need to study future disease trends at different spatial and temporal scales (Juroszek and von Tiedemann 2013).

One of the major problems in peanut consumption is the presence of aflatoxin (i.e. toxins produced by certain fungi) which could lead to cancer and could even cause death due to aflatoxicosis. The latest major outbreak of aflatoxicosis occurred in Kenya between 2004 and 2006, and claimed the lives of more than 150 people (Mutegi et al. 2012). The first aflatoxicosis outbreak, known as the "Turkey X" disease epidemic, occurred in England in 1961 due to the imported groundnut ingredients in bird feed. The hepatotoxic product of *aspergillus* species found in the feed was concluded to be the agent responsible for the disease (Blount 1961). This toxin was subsequently named aflatoxin (Blount 1961), which is a secondary metabolite produced by common soil fungi, namely *aspergillus* (Perrone et al. 2014). There are four major aflatoxins: aflatoxins B_1, B_2, G_1, and G_2, which occur naturally in agro-products (Klich 2007). Of these, aflatoxin B_1 is the most toxic (Zorzete et al. 2011). Evidence indicates that aflatoxins B_1 and G_1 have carcinogenic potential and have been categorised by the International Agency for Research on Cancer (IARC) as a group 1 human carcinogen (IARC 2012), that is, a group of agents with sufficient evidence of causing cancer in humans (IARC 2006).

Due to the adverse effects of aflatoxin contamination in human health, the maximum acceptable level of aflatoxin in agricultural products has been regulated in more than 120 countries (Bui-Klimke et al. 2014). For example, the European Union, known as the major peanut importer for some of its member countries (Fletcher and Shi 2016), regulated the maximum level of aflatoxin B_1 and other aflatoxin types in groundnuts at 2 and 4 µg/kg, respectively (EC-European Commission 2010). The regulations of aflatoxin level would induce significant economic losses if the maximum acceptable level could not be achieved. Wu (2004) found that the peanut industries in USA, China, Argentina, and Africa would suffer around $450 million annual losses if the European standard of aflatoxin maximum limit was applied.

Two *aspergillus* species, i.e. *aspergillus flavus* and *aspergillus paraciticus*, are associated with aflatoxin infection in agricultural crops (Perrone et al. 2014). *Aspergillus flavus* has been identified as the major vector for aflatoxin infection (Torres et al. 2014). Aflatoxin commonly infects crops such as peanut (*Arachis hypogaea* L), corn (*Zea mays* L), and cottonseeds (*Gossypium*) which are grown in the latitudes where *aspergillus* species is commonly found (Klich 2007). Klich (2002) revealed that while *aspergillus* species persists at projected frequencies in tropical latitudes, i.e. below 25 degrees of south and north, and is found more frequently in the subtropical or warm temperate zones of 26-35 degrees, it hardly persists in higher latitudes. It is suggested that differences in the temperature at those latitudes might be the factor for these differences in persistence (Klich 2002). The optimal temperatures for *aspergillus* development are between 25 and

40°C, while the minimum temperature for its growth is 10°C (Klich et al. 1992). This optimal temperature range persists in the subtropical or warm temperate zone for a relatively long period, which explains the persistence of *aspergillus* species in this zone (Klich 2002).

Fortunately, the presence of *aspergillus* in the crops does not necessarily indicate the occurrence of aflatoxin (Hill et al. 1983). Certain environmental stresses, e.g. temperature increase and prolonged drought, are required for the infection to occur (Cole et al. 1989; Cotty and Jaime-Garcia 2007). The longer the crops are exposed to environmental stresses and other risk factors (e.g. high soil insect incidence), the greater the probability of aflatoxin infection (Rachaputi et al. 2002). In addition, agricultural practices, such as adapted cultivars, seed density, fertilization (especially nitrogen), irrigation, and harvesting time (Klich 2007), also determine the infection rate of aflatoxin (Horn and Dorner 1999). However, climate is the main driving factor for aflatoxin contamination (Paterson and Lima 2010).

Peanut crops are one of the legume crops. They are unique because the flowers are above ground, but once pollinated, they produce fruits below the surface of the soil (Stalker 1997). As a result, peanut fruits have direct contact with soil microorganisms, including the vector for aflatoxin infection, *aspergillus* fungus (Guo et al. 2003). Consequently, the fruits have a high-risk of aflatoxin contamination (Zorzete et al. 2011). Schroeder and Boller (1973) found that peanut is one of the most suitable substrates for high aflatoxin production. Prolonged heat and drought stress during the last 4 to 6 weeks of the peanut growing season facilitate the synthesis of aflatoxin in peanut seeds (Chauhan et al. 2010), and result in pre-harvest contamination. Aflatoxin contamination could also occur at the post-harvest stage (Torres et al. 2014), but in general, pre-harvest contamination is still the dominant factor in aflatoxin infection in peanut crops (Cole et al. 1989).

As both aflatoxin occurrence and severity depend on climate stresses, changes in climate could affect aflatoxin contamination in agricultural crops, including peanut. One of the methods to evaluate the impact of climate change in the geographic distribution of aflatoxin is the use of Species Distribution Models (SDMs), such as CLIMatic indEX or CLIMEX (Sutherst and Maywald 1985). CLIMEX is a mechanistic or process-oriented computer model which is designed to explore the effects of climate on species (Kriticos and Leriche 2010). A set of species growth and stress functions is used in assessing the response of species to climate variables and their ability to persist in a location. The model has been used successfully in a wide range of taxa, including plants, pathogens, mammals, and insects (Kriticos and Leriche 2010). It is also well suited to model invasive species (Kriticos et al. 2013). Some examples of successful applications of the CLIMEX model include the study of future distribution of another legume crop, the common bean (*Phaseolus vulgaris* L.) (Ramirez-Cabral et al. 2016) and the study of *Fusarium oxysporum* f. spp. pathogen (Shabani et al. 2014).

Australia has experienced an average temperature increase of 0.9°C from 1910 to 2009, which is projected to continue up to 1.0°C by 2030 (Cleugh et al. 2011). The country is also known for its high climate variability and is likely to suffer more frequent extreme events, such as drought, heat-waves, and floods (Head et al. 2014). There is also a projection of summer rainfall uncertainty in northern Australia (Cleugh et al. 2011), where the majority of peanut crops is grown. These climate change projections have placed peanut crops in Australia in a vulnerable position for aflatoxin contamination and could affect the geographical distribution of aflatoxin. Therefore, further investigation in this area is undoubtedly important. The primary aim of this study was to examine the effect of climate change on the future distribution of aflatoxin in peanut crops in Australia. The following are the specific objectives: 1) to develop CLIMEX model parameters of aflatoxin disease in peanut crops; and 2) to identify the projected distribution of aflatoxin in Australia under climate models.

2. Materials and methods

2.1. Study area

The study covers the Australian continent encompassing a total area of 7.692 million km^2 (Geoscience Australia 2018) (Fig. 1). The major climate types in Australia are tropical, subtropical, desert, grassland/semi-arid, and temperate (Kriticos et al. 2012). These climate types are based on the Koppen-Geiger classification, following the application of the rules of Kriticos et al. (2012) applied to the 5’ resolution of WorldClim – Global Climate Data (Hijmans et al. 2005). Agricultural activities are prevalent in the eastern parts of Queensland and New South Wales, most of Victoria, the southern part of South Australia, and the south-western part of Western Australia (ABARES 2019). Generally, peanut crops are grown under dry culture practice on large scale farms with fully mechanized systems (Pitt and Hocking 2006). The cultivation areas spread across the eastern part of Queensland and the northern part of the Northern Territory (Chauhan et al. 2013; Crosthwaite 1994). Unfortunately, aflatoxin contamination in peanut is the dominant mycotoxin problem in Australia (Pitt and Hocking 2006). In a study, Hansen and Norman (1999) revealed the historical level of aflatoxin contamination in dryland South and Central Burnett, the Atherton Tableland, and the Northern Territory as 42%, 11%, and 17%, respectively, which generated economic loss. In fact, for some extreme climate conditions, almost 100% of peanut from dryland South and Central Burnett may be contaminated with aflatoxin (Hansen and Norman 1999).

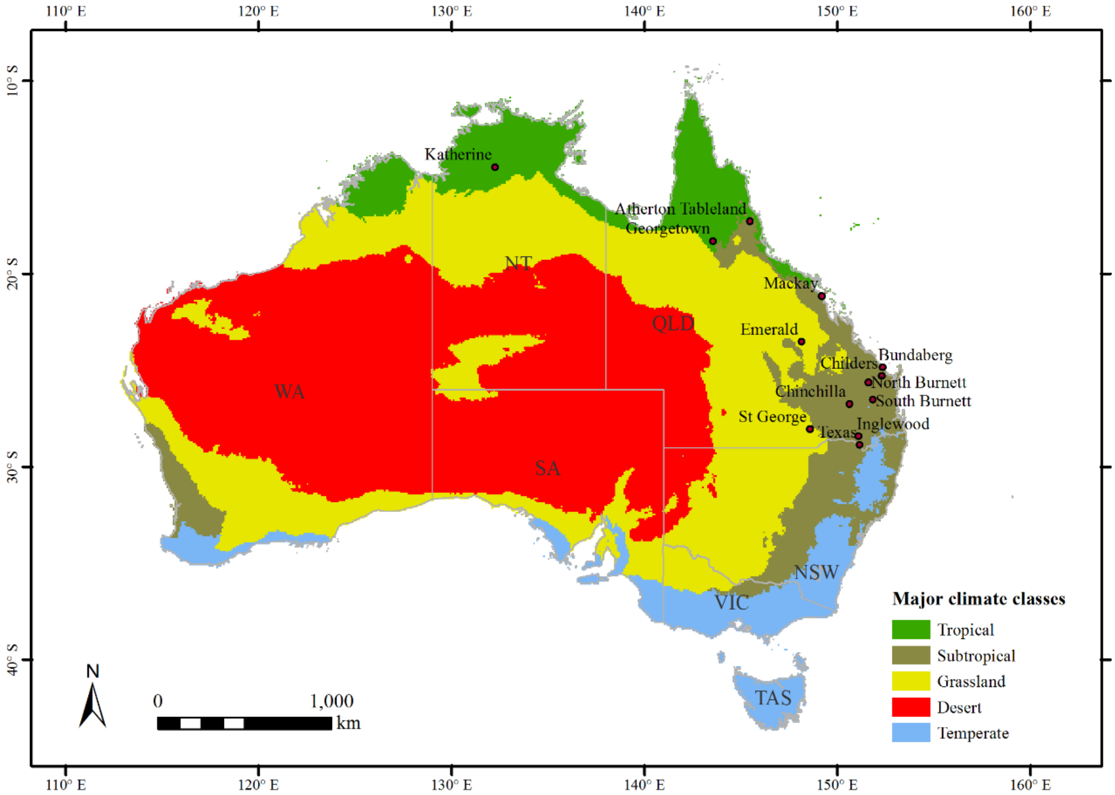


Fig. 1 Study area (Australia) and current cultivation areas of peanut crops (red circles) throughout different climate classes based on Kriticos et al. (2012) rule

2.2. Research flowchart

The workflow of this study is presented in Fig. 3.

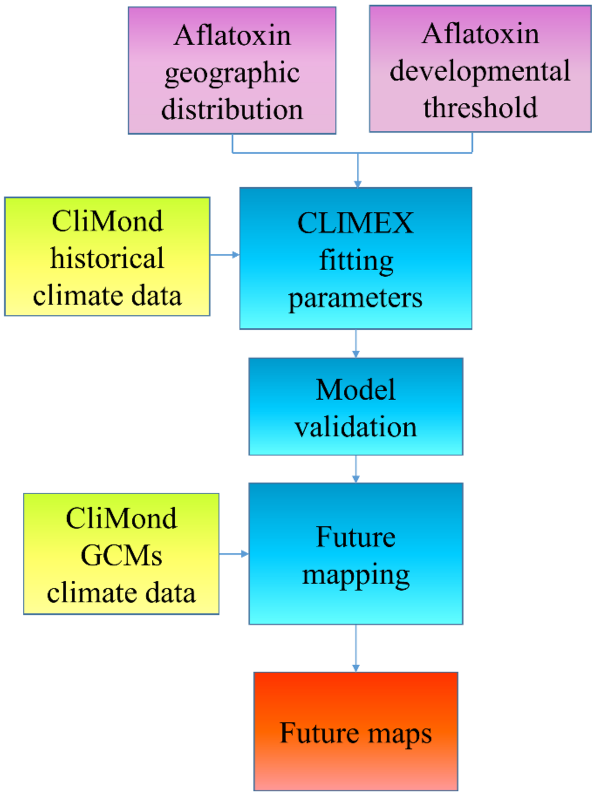


Fig. 3 The study flowchart and key processing tasks

2.3.Global geographic distributions of aflatoxin

Evidence concerning the global distribution of aflatoxin incidence was retrieved from various academic articles. Aflatoxin incidence spreads across tropical, sub-tropical and semi-arid climates in America, Africa, Asia, Europe, and Australia (Fig. 2). In total, there were 405 recorded locations of aflatoxin outbreaks, with 151 locations in Asia, 150 locations in Africa, 87 locations in America, 12 locations in Italy, Europe, and 5 locations in Australia. Specifically, the locations of aflatoxin data were retrieved from the following academic papers: Kenya (Collins et al. 2010; Lewis et al. 2005; Mutegi et al. 2012); Zambia (Kachapulula et al. 2017); Ghana (Agbetiameh et al. 2018); Ethiopia (Chala et al. 2013; Chauhan et al. 2016); Mali (Waliyar et al. 2015); Democratic Republic of Congo (Kamika and Takoy 2011; Kamika and Tekere 2016); Malawi (Waliyar et al. 2013);

Nigeria (Bankole and Mabekoje 2004); Tanzania (Seetha et al. 2017); Benin (Setamou et al. 1997); Uganda (Kaaya et al. 2006); the Philippines (Arim 2000; Arim 2003; Quitco 1991; Yamashita et al. 1995); Indonesia (Ali et al. 1998; Rahayu et al. 2003; Yamashita et al. 1995); Thailand (Siriacha et al. 1988; Yamashita et al. 1995); India (Kishore et al. 2002; Sharma and Parisi 2017; Shinha 1990; Vijayasamundeeswari et al. 2009); China (Daren 1989; Li et al. 2001; Wu et al. 2016; Zhang et al. 2011); the USA (Horn et al. 1995; Pettit et al. 1971); Brazil (Atayde et al. 2012; Gonçalez et al. 2008; Moreno et al. 2009; Rocha et al. 2009); Argentina (Barros et al. 2003; Resnik et al. 1996); Costa Rica (Mora and Lacey 1997); Mexico (García and Heredia 2006); Italy (Battilani et al. 2013); Australia (Chauhan et al. 2010). The global distribution data were divided into two groups, one for parameter fitting and the other one for model validation.

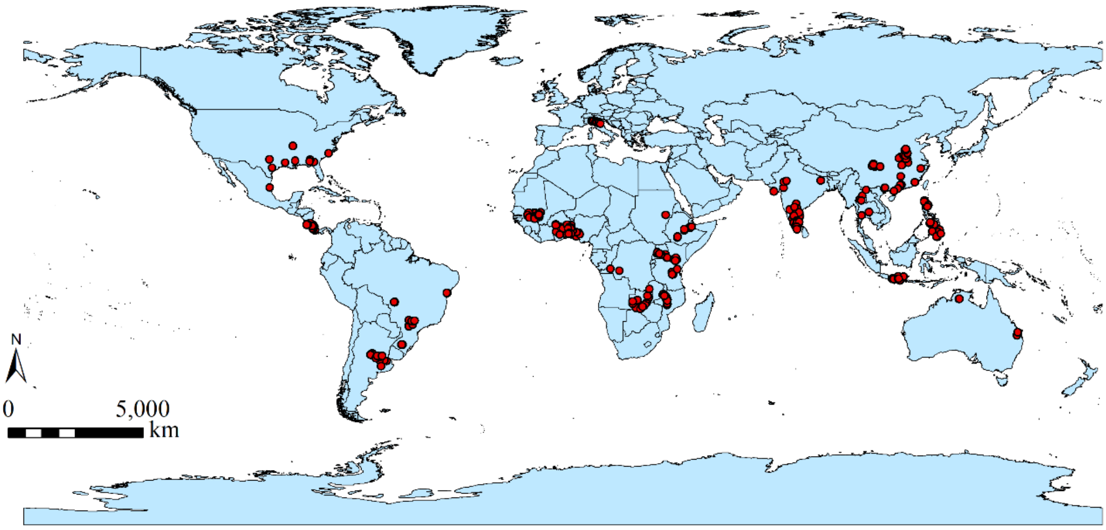


Fig. 2 The distribution of aflatoxin outbreaks throughout the world from various academic papers. Red circles represent the distribution data

2.4. Meteorological database and climate change models

CliMond 10’ (18.55km) resolution climate database (Kriticos et al. 2012) was used in this study to provide historical and future climatic variables required for CLIMEX modelling of aflatoxin distribution. The climatic variables for the CLIMEX model consist of average maximum monthly temperature (T_{max}), average minimum monthly temperature (T_{min}), average monthly precipitation (P_{total}) and relative humidity recorded at 9am ($RH_{09:00}$) and 3pm ($RH_{15:00}$) (Kriticos et al. 2015). The historical climate data were retrieved from 1950 to 2000, centred at 1975 (Kriticos et al. 2012).

The future climate was modelled using two Global Climate Models (GCMs), namely CSIRO-Mk3.0 (developed by CSIRO, Australia) and MIROC-H (developed by the Centre for Climate Research, Japan). They were obtained from the CliMond database. The choice of these GCMs was based on the following criteria: (1) the ability to provide monthly averages of daily maximum and minimum temperatures, precipitation, mean sea level pressure, and specific humidity; (2) having a relatively smaller-horizontal grid spacing (e.g. less than 2×2° over Australia); and (3) providing relatively good performance at a regional scale compared to other GCMs in representing basic aspects of the observed climates (Kriticos et al. 2012).

The future aflatoxin distributions were modelled using the Special Report on Emission Scenarios (SRES) A2 and A1B family (Nakicenovic et al. 2000) retrieved from the CliMond database. The latest Intergovernmental Panel on Climate Change (IPCC) report of the AR5 Synthesis Report has disclosed the new climate scenarios, namely the Representative Concentration Pathways (RCPs). This consists of RCP8.5, RCP6, RCP4.5, and RCP2.6. The closest similar RCP scenario to SRES A2 is RCP8.5, which depicts the worst-case scenario with a high emission. Meanwhile, SRES A1B resembles RCP6.0, which represents an intermediate emission pathway (Van Vuuren and Carter 2014; Van Vuuren et al. 2011). The temperature increase at the end of the 21st century (relative to 1980-1999) for SRES A2 is projected to be 3.4°C with a likelihood ranging from 2.0°C to 5.4°C (Bernstein et al. 2008); while for RCP8.5, it is projected to be 3.7°C with a range of 2.6 – 4.8°C (relative to 1986-2005) (IPCC 2014). In the case of SRES A1B, the temperature is projected to increase by 2.8°C with a range of 1.7 – 4.4°C by the end of 21st century (relative to 1980-1999) (Bernstein et al. 2008). Meanwhile, the temperature increase of RCP6.0 at the end of the of 21st century (relative to 1986-2005) is projected to be 2.2°C with a range of 1.4 – 3.1°C (IPCC 2014).

2.5.CLIMEX model

The CLIMEX program is a simplified dynamic model that infers the response of species to climatic conditions, based on their geographical distribution and their growth and mortality patterns (Kriticos et al. 2015). There are several modes of CLIMEX program, and this study used the 'compare locations' mode. The program is run by determining a set of parameter values that reveals species' response to temperature, soil moisture, and if applicable, light (Kriticos et al. 2015). These values reflect the climatic conditions that favour species growth and limit species survival (Sutherst and Bourne 2009) and are calculated weekly in the form of Growth Index (GI_W) and Stress Index (SI_W). The Growth Index determines species' population growth, and consists of two parameters: Temperature Index (TI) and Moisture Index (MI). The Stress Index leads to species' negative population growth, and is calculated from Cold Stress (CS), Heat Stress (HS), Dry Stress (DS), and Wet Stress (WS) parameters (Kriticos et al. 2015; Sutherst and Maywald 1985). The weekly indices of GI_W and SI_W are then combined into annual value (GI_A and SI_A) to calculate the value of Ecoclimatic Index (EI).

The EI value shows favourable conditions for a species to persist in a location, with a range from 1 (indicates unsuitable conditions for species persistence) to 100 (indicates optimal conditions for species persistence) (Kriticos et al. 2015; Sutherst and Maywald 1985). As with most of the CLIMEX studies, this study classifies EI value into four categories: unsuitable (EI = 0), marginal (0<EI<10), suitable (10<EI<20), and optimal (EI>20). The CLIMEX functions are calculated as follows (Kriticos et al. 2015):

$$EI = GI_A \times SI_A \quad (1)$$

where:

GI_A, the annual Growth Index $= 100 \sum_{i=1}^{52} GI_w / 52$ (2)

GI_W, the weekly Growth Index $= TI_W \times MI_W$ (3)

TI_W is weekly Temperature Index and MI_W is weekly Moisture Index

SI_A, the annual Stress Index, $= \left[\left(1 - \frac{CS}{100}\right) \times \left(1 - \frac{DS}{100}\right) \times \left(1 - \frac{HS}{100}\right) \times \left(1 - \frac{WS}{100}\right)\right]$ (4)

CS, DS, HS, WS, respectively are the annual cold, dry, heat, and wet stress indices.

2.6. Adjustment of CLIMEX parameters

The CLIMEX parameters have to fit the geographical distribution and be biologically reasonable, based on the theoretical and experimental domains of the species (Kriticos et al. 2015). As a result, the parameter fitting in this study was developed based on: (1) aflatoxin developmental threshold of temperature and moisture level from various academic literature and (2) the global geographical distribution of aflatoxin as provided in section 2.2. The aflatoxin distribution data in the African and American continents were used in the parameter fitting process of this study.

The CLIMEX program provided several parameter templates representing different geographical distributions. These templates could be used as a starting point to develop CLIMEX parameters (Kriticos et al. 2015). The CLIMEX parameter template used in this study was determined based on the comparison between the aflatoxin distribution map and the distribution map retrieved from all templates. The CLIMEX parameter template which showed the closest distribution with aflatoxin distribution was ‘wet tropical template'. As a result, this template was used as a basis in developing the CLIMEX parameters of aflatoxin.

The starting point to fit the CLIMEX parameters was the adjustment of Stress Indices rather than Growth Indices. The purpose of this step was to recognise the unsuitable areas of aflatoxin persistence in the wet tropical template; thus the boundary of aflatoxin distribution could be set. The process of these adjustments was carried out iteratively by comparing the CLIMEX model output with the geographical distribution of aflatoxin. Afterwards, Growth Indices were developed using the same iterative fitting procedures. The developmental threshold acquired from academic literature was used as a basis to fit these CLIMEX parameters. The parameter adjustment process was carried out iteratively until an agreement between the CLIMEX model output and aflatoxin geographical distribution was achieved (Kriticos et al. 2015). The final parameters (Table 1) were then used to develop future aflatoxin models in Australia in relation to climate change occurrences.

Based on the analysis of wet tropical template and aflatoxin distribution maps, it can be resolved that most of the excluded aflatoxin distribution in the wet tropical template was due to the presence of cold and dry stresses. Therefore, the fitting process for CLIMEX aflatoxin parameters was started by adjusting cold and dry stress parameters. Below is the detailed explanation on the process of CLIMEX parameters determination.

Cold stress: In order to incorporate the aflatoxin occupation areas in the USA, China, and Argentina into the CLIMEX aflatoxin model, the Cold Stress Day-degree Threshold (DTCS) and the Cold Stress Degree-day Rate (DHCS) were set at 15°C and -0.00012 week^{-1}, respectively.

Dry stress: Determination of the Dry Stress Threshold (SMDS) was based on the value of permanent wilting point of crops, i.e. 0.1. Meanwhile, in order to include the aflatoxin occupation areas in Mali, Sudan, and Zambia, the Dry Stress Rate (HDS) was set to -0.00008 week^{-1}.

Heat stress: The Heat Stress Temperature Threshold (TTHS) and the Heat Stress Temperature Rate (THHS) were determined at 40°C and 0.00009 week^{-1}, respectively, to allow the inclusion of aflatoxin incidence in Mali and Sudan.

Wet stress: In order to eliminate wet stress incidents in aflatoxin geographic distribution, the Wet Stress Threshold (SMWS) and the Wet Stress Rate (HWS) were set at 2 and 0.0009, respectively.

Temperature index: The temperature range which supports aflatoxin growth and development was parameterised in the CLIMEX model as a limiting low temperature (DV0), a lower optimal temperature (DV1), an upper optimal temperature (DV2), and a limiting high temperature (DV3). Since peanut fruits are underground, the aflatoxin temperature range for peanut crops is mostly measured at the fruiting zone, known as the geocarposphere (Smartt 2012), i.e. 5 cm below the soil surface. On average, air temperature is lower (4 to 6°C), compared to the temperature of the geocarposphere (Smartt 2012).

Unfavourable geocarposphere temperatures for aflatoxin development in peanut are found to be 23.6°C or lower (Blankenship et al. 1984) and 24.6°C (Cole et al. 1985), which are around air temperature of 17.6°C to 20.6°C. Therefore, after iteratively fitting CLIMEX parameters, DV0 was determined at 17.5°C. In regard to optimum temperature for aflatoxin incidence in peanut crops, favourable geocarposphere temperatures are 26.3 - 29.6°C (Cole et al. 1985), 28 – 30.5°C (Sanders et al. 1985), and 25 - 28°C (Hill et al. 1983). Based on these data and the iterative fitting parameter process, DV1 and DV2 were set at geocarposphere temperature of 26°C and 30.5°C or 20°C and 24.5°C air temperature. In terms of maximum temperature for aflatoxin occupation, Chauhan et al.

(2008) set the temperature at 35°C, while Gallo et al. (2016) found aflatoxin contamination at almonds was halted at 37°C. Therefore, to include the aflatoxin areas in Mali and Sudan, DV3 was set to be 38°C.

Moisture index: The limiting low moisture (SM0) of CLIMEX parameter of aflatoxin was set according to permanent wilting point, i.e. 0.1 or 10% of soil moisture. In a study, Chauhan et al. (2008) identified that aflatoxin accumulated at less than 20% of soil moisture, while Sanders et al. (1985) indicated that moisture tension bars of 2.9 (around 84% of soil moisture) did not stimulate aflatoxin contamination in peanut crops. Therefore, after being iteratively adjusted, the lower and upper optimal moisture (SM1 and SM2) were set at 0.2 and 0.8, respectively. Meanwhile, to prevent wet stress occurrence in aflatoxin distribution areas, the limiting high moisture (SM3) was set to be similar to the Wet Stress Threshold (SMWS), i.e. 2.

Table 1 CLIMEX parameter values generated from this study and used in modelling aflatoxin distribution

Index	Parameters	Values
Temperature	DV0	17.5°C
	DV1	20°C
	DV2	24.5°C
	DV3	38°C
Moisture	SM0	0.1
	SM1	0.2
	SM2	0.8
	SM3	2
Cold stress	DTCS	15°C
	DHCS	-0.00012 week^{-1}
Heat stress	TTHS	40°C
	THHS	0.00009 week^{-1}
Dry stress	SMDS	0.1
	HDS	-0.00008 week^{-1}
Wet stress	SMWS	2
	HWS	0.0009 week^{-1}

2.7. Model validation

Geographic distribution data of aflatoxin incidence in India, China, the Philippines, Thailand, Indonesia, Italy, and Australia were not used in model development, but were reserved for model validation purposes. This decision was taken to ensure model performance and reliability.

3. Results

3.1. Model evaluation and current climate

The CLIMEX aflatoxin model result shows a consistency with the global distribution data of aflatoxin (Fig. 4). None of the aflatoxin geographic distribution data were categorised as unsuitable areas for aflatoxin occurrence. Indeed, most of the distribution data were included in optimal areas of the model. For example, most aflatoxin data in the American continent were categorised in optimal areas, while only small amounts were incorporated in suitable areas. None of them were included in marginal or unsuitable areas. Cold stress was found to be the major obstacle for further aflatoxin occupation in the northern and southern part of the continent (Fig. 5a). In the case of the African continent, the majority of distribution data were included in optimal areas for aflatoxin persistence. Meanwhile, some of the distribution data were fitted to suitable areas of the CLIMEX aflatoxin model, i.e. distribution data in the northern part of Ghana, northern part of Benin, and most of Mali. Only a small portion of aflatoxin incidence in Mali and Sudan were incorporated in marginal areas, merely due to their closeness with areas suffering dry and heat stresses in the northern part of Africa (Fig. 5b and 5c).

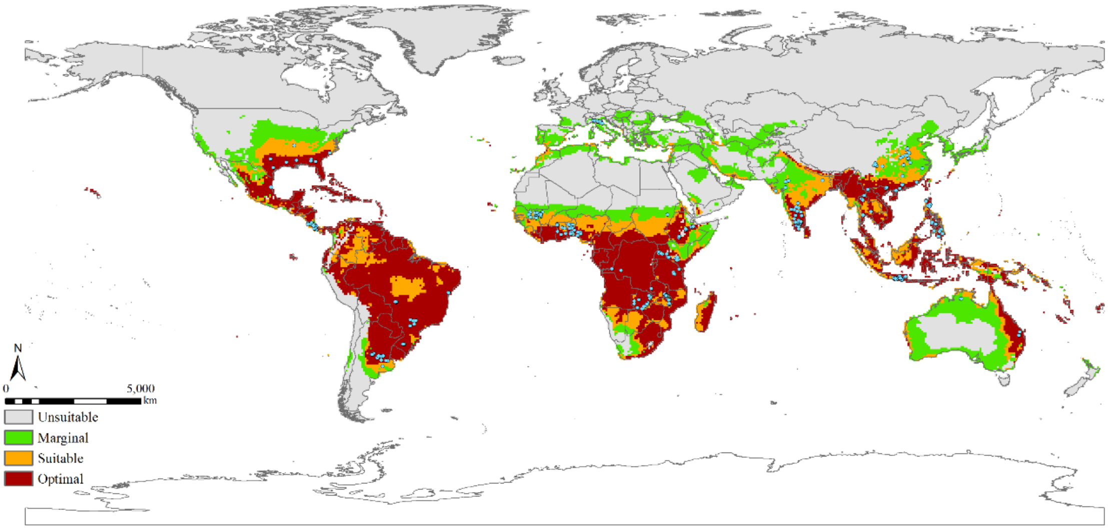
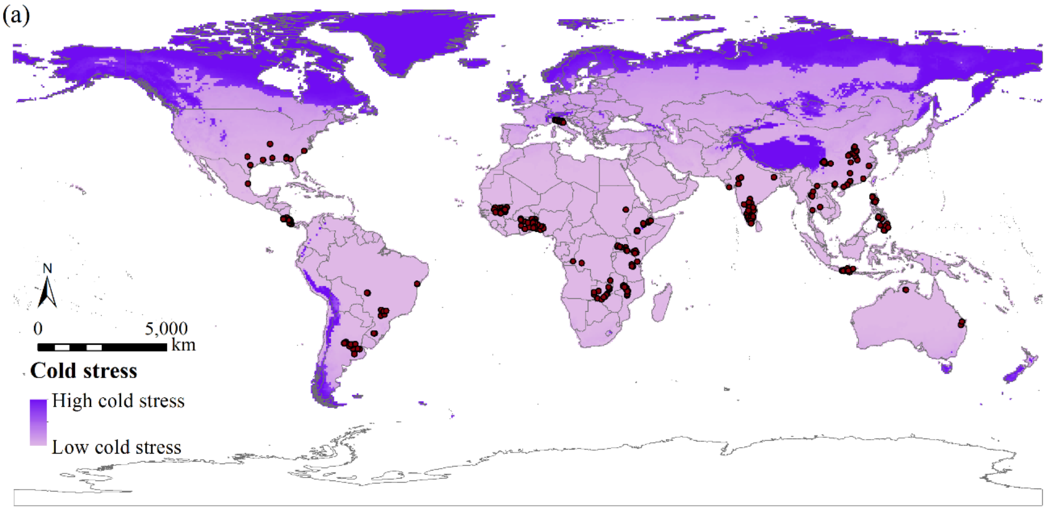
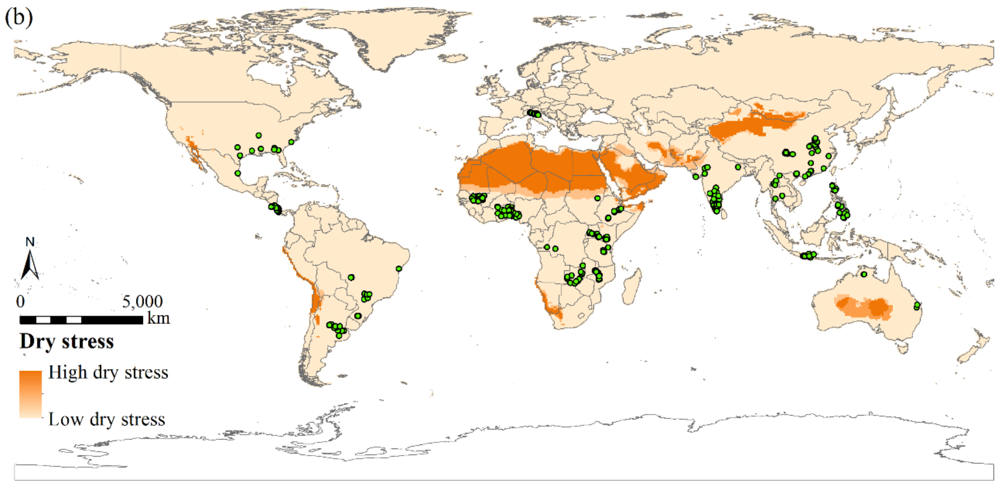


Fig. 4 CLIMEX model output of Ecoclimatic Index (EI) of aflatoxin using current climate data. Blue circles represent the current distribution of aflatoxin

(a)





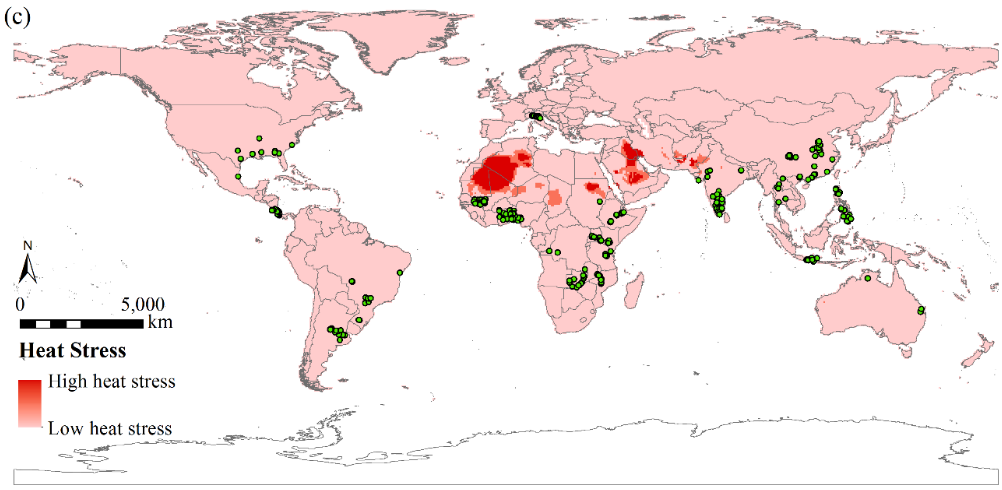


Fig. 5 Map of cold stress (a), dry stress (b), and heat stress (c) of aflatoxin CLIMEX model. Green and red circles represent global geographical distribution of aflatoxin

Aflatoxin distribution in model validation areas (India, China, the Philippines, Thailand, Indonesia, Italy, and Australia) showed agreement with the distribution in the model development areas (the American and African continents). Fig. 6 showed that most of the distribution data in the validation areas were categorised as optimal in the aflatoxin model, especially those in tropical climate regions, such as Indonesia, Thailand, and the Philippines. Some of the subtropical and semi-arid distribution areas in China, India, Australia, and Italy were in suitable or marginal categories. None of the distribution data were categorised as unsuitable areas for aflatoxin occupation. Adjusting cold stress parameters to include the northern and southern distribution points of the American continent in the subtropical climate into the aflatoxin CLIMEX model had also enabled the inclusion of similar climate types of validation areas in the northern distribution points of China. Similarly, the inclusion of northern point distribution of the African continent was carried out by adjusting heat and dry stress parameters, which automatically resulted in the inclusion of aflatoxin distribution in validation areas of India, i.e. Rajasthan, Bihar, and Gujarat. Both of the areas in Africa and India have grassland or semi-arid climates.

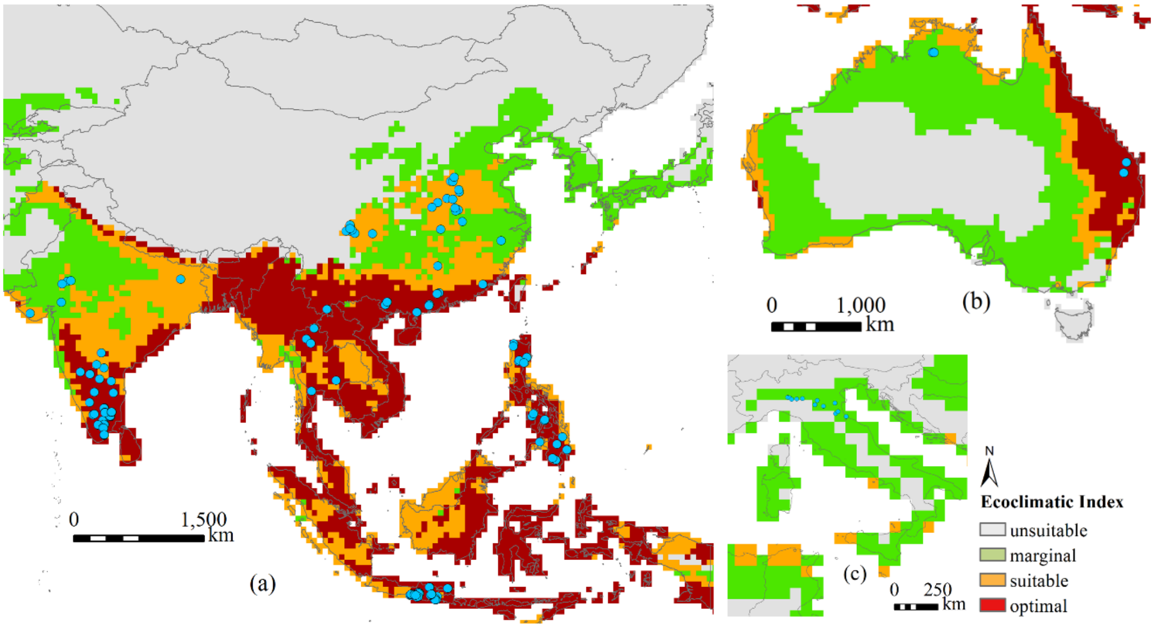


Fig. 6 CLIMEX model output of Ecoclimatic Index (EI) of aflatoxin in validation areas of (a) Asia, (b) Australia, and (c) Italy. Blue circles represent the current distribution of aflatoxin

Based on the global distribution of aflatoxin (Figure 2), it can be seen that aflatoxin occurs between 40° North latitude and 40° South latitude. The majority of aflatoxin incidence occurred in tropical and subtropical climate zones, although some incidents were also found in the semi-arid grassland climate zone. Interestingly, the majority of aflatoxin distribution in tropical regions, such as the central part of the African continent, Brazil, India, Thailand, Indonesia, and the Philippines, were categorised as optimal areas in the CLIMEX model. Similarly, most of the distribution of aflatoxin in subtropical regions was in optimal areas for aflatoxin incidence, i.e. distributions in the USA, Argentina, Zambia, and Australia. However, some of the distributions in this subtropical zone were also categorised in suitable areas of the CLIMEX model, such as most of the aflatoxin distribution in China. Only a small number of distributions in the subtropical regions were included in marginal areas for aflatoxin persistence, for example aflatoxin distribution in Italy. In terms of aflatoxin distribution in semi-arid climate regions, only a small proportion occurred. The majority of distributions in this climate region was categorised as suitable and marginal areas in the CLIMEX model, except for small distributions in India which were categorised as optimal areas.

3.2. Future projections

Using the CLIMEX model, the projected aflatoxin areas in Australia under the CSIRO-Mk3.0 climate model based on SRES A2 and SRES A1B climate scenarios are presented in Fig. 7 and Fig. 8. In general, the majority of the Australian continent is categorised as unsuitable areas for aflatoxin contamination. This includes arid climate region in the middle, north, and north-western part of Australia. It is projected that under the CSIRO-Mk3.0 model, the number of unsuitable areas will increase significantly from 2030 to 2100, due to the conversion of marginal areas into unsuitable areas. Most of these marginal areas are also characterised by the arid climate type.

Meanwhile, only small areas of Australia are categorised as optimal and suitable for aflatoxin infection. The majority of these categories are located in the eastern part of Australia, while small numbers are located in the south-western part of Western Australia. Both of these areas are included as subtropical and temperate climate regions. In contrast to unsuitable areas, the projections of optimal and suitable areas show a remarkable reduction trend from 2030 to 2100. Although the number of optimal and suitable areas in the subtropical region of north-eastern part of Australia are reduced at the latter period of the projection years, the optimal and suitable areas in the temperate region of south-eastern and south-western part of Australia have increased. Interestingly, when comparing the projections of the worst climate scenario (SRES A2) and the intermediate climate scenario (SRES A1B), not many differences were observed throughout the projection years. The only noticeable difference appeared in 2100, where some of unsuitable areas in the worst case scenario projection are projected to be marginal in the intermediate scenario.

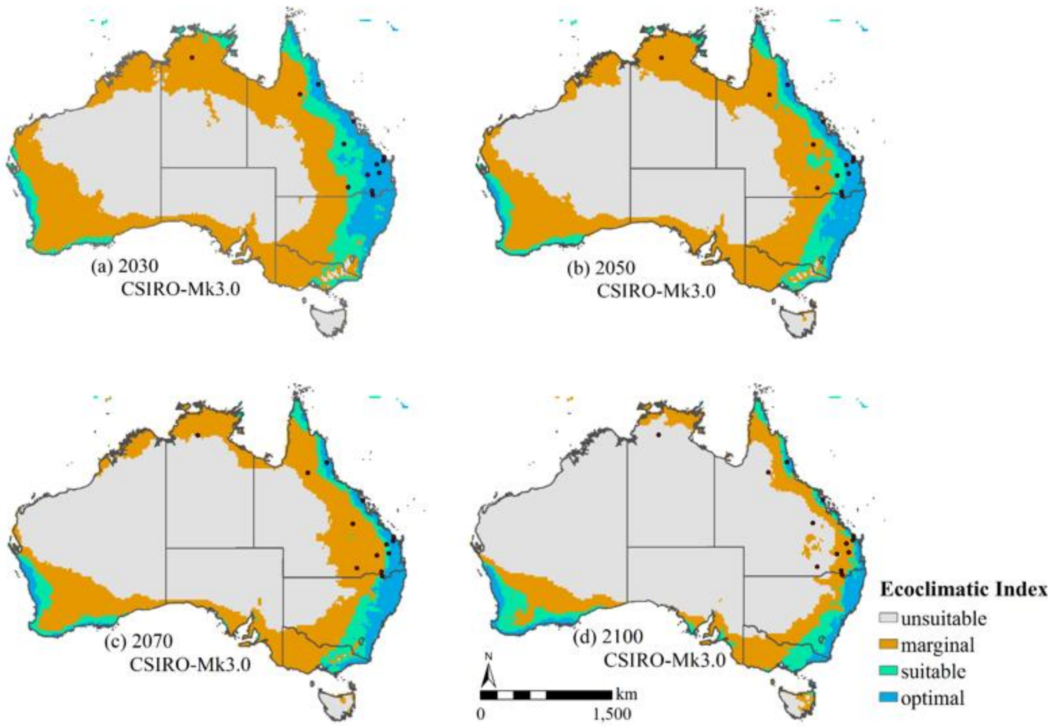


Fig. 7 The future aflatoxin distributions in Australia using CLIMEX model under CSIRO-Mk3.0 Global Climate Model with SRES A2 climate scenario. Red dots represent distribution areas of peanut crops

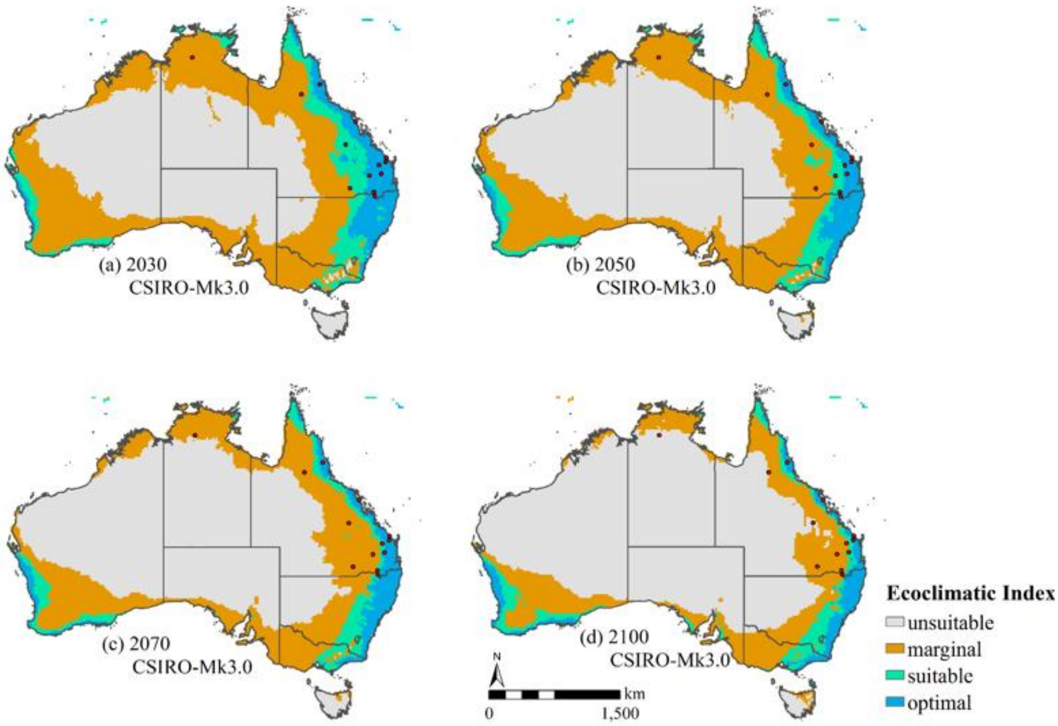


Fig. 8 The future aflatoxin distributions in Australia using CLIMEX model under CSIRO-Mk3.0 Global Climate Model with SRES A1B climate scenario. Red dots represent distribution areas of peanut crops

The results of the MIROC-H climate model projections of aflatoxin based on SRES A2 and SRES A1B scenarios by using the CLIMEX model are shown in Fig. 9 and Fig. 10. In a similar way to CSIRO-Mk3.0, the projections of the MIROC-H climate model are dominated by unsuitable areas for aflatoxin occupation, but with a smaller area. In addition, unlike CSIRO-Mk3.0, the increase of unsuitable areas of MIROC-H throughout the projection years is slight. The results show that unsuitable and marginal areas are mainly located in arid climate zones (grassland/semi-arid and desert) of Australia, i.e. in the middle, north, and north-western areas. Although some marginal areas in the northern part of Australia are converted into unsuitable areas in the latter period of the projection years, some parts of the unsuitable areas in the semi-arid regions of middle Australia are converted into marginal areas. However, overall, there is a decrease in the marginal areas.

In a similar way to CSIRO-Mk3.0, the majority of optimal and suitable areas for aflatoxin contamination under the MIROC-H model are located in the eastern part of Australia. Some of these areas can also be found along the coast of Western Australia. Although the optimal and suitable areas for the CSIRO-MK3.0 and MIROC-H models show no significant difference in 2030, there is a substantial variation in areas following the projection years. MIROC-H projected an increase of optimal and suitable areas in the south-eastern, south-western, and southern part of Australia, which are mainly categorised as temperate regions. Comparing the two scenarios, i.e. SRES A2 and SRES A1B, the differences were only observed in 2070 and 2100 projection years.

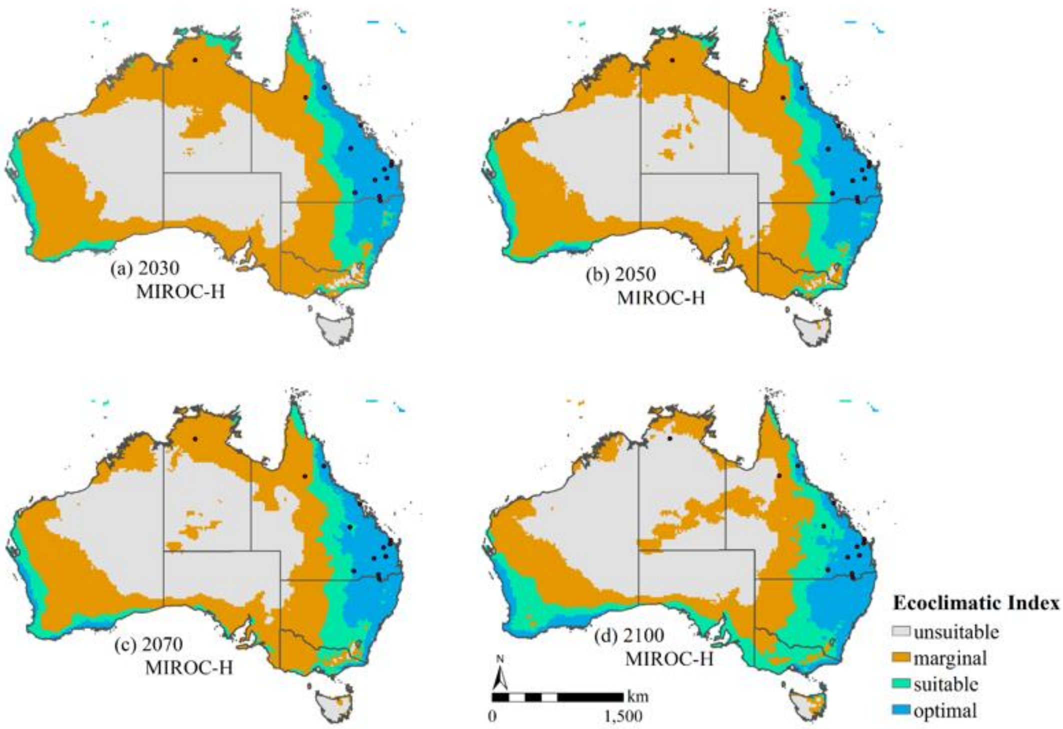


Fig. 9 The future aflatoxin distributions in Australia using CLIMEX model under MIROC-H Global Climate Model with SRES A2 climate scenario. Red dots represent distribution areas of peanut crops

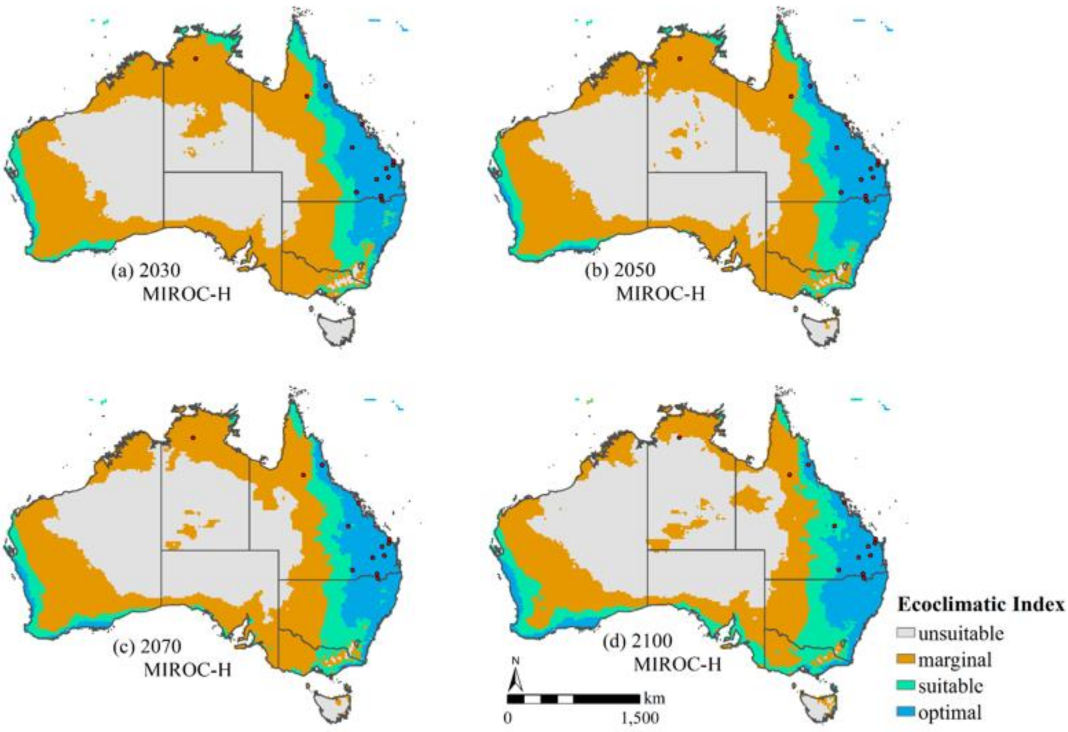


Fig. 10 The future aflatoxin distributions in Australia using CLIMEX model under MIROC-H Global Climate Model with SRES A1B climate scenario. Red dots represent distribution areas of peanut crops

Table 2 The percentage of projected optimal, suitable, marginal, and unsuitable areas for aflatoxin contamination in Australia continent under CSIRO-Mk3.0 (CS) and MIROC-H (MR) based on SRES A2 scenario

CLIMEX	2030		2050		2070		2100	
output	CS (%)	MR (%)	CS (%)	MR (%)	CS (%)	MR (%)	CS (%)	MR (%)
Optimal	7	10	6	10	5	11	4	12
Suitable	9	10	7	10	6	11	6	15
Marginal	38	43	35	41	28	37	16	30
Unsuitable	46	37	52	39	61	41	74	43

Table 3 The percentage of projected optimal, suitable, marginal, and unsuitable areas for aflatoxin contamination in Australia continent under CSIRO-Mk3.0 (CS) and MIROC-H (MR) based on SRES A1B scenario

CLIMEX	2030		2050		2070		2100	
output	CS (%)	MR (%)	CS (%)	MR (%)	CS (%)	MR (%)	CS (%)	MR (%)
Optimal	7	10	6	10	5	11	5	11
Suitable	9	10	7	10	6	11	6	13
Marginal	37	43	33	41	29	38	22	33
Unsuitable	47	37	54	39	60	40	67	43

Table 2 and Table 3 show the percentage of projected optimal, suitable, marginal, and unsuitable areas for aflatoxin contamination in Australia. Looking at the difference between the projection results of CSIRO-Mk3.0 and MIROC-H, it can be said that optimal, suitable, and marginal areas for aflatoxin contamination of MIROC-H model are higher than CSIRO-Mk3.0 model, with an increase in difference gaps throughout the projection years. On the contrary, unsuitable area percentages of CSIRO-Mk3.0 are higher than MIROC-H throughout the projection years, also with an increase in difference gaps.

The majority of the Australian continent is projected to be unsuitable for aflatoxin contamination under the CSIRO-Mk3.0 and MIROC-H climate models. CSIRO-Mk3.0 projections based on SRES A2 and SRES A1B show a significant increase (up to 61 and 43%, respectively) of unsuitable areas, from 46 and 47% of the Australian continent (3.53 and 3.61 million km^2) in 2030 to 74 and 67% of the Australian continent (5.69 and 5.15 million km^2) in 2100, respectively. Meanwhile, for both scenarios, MIROC-H only shows a slight increase (up to 16%) of unsuitable areas from 37% of the Australian continent (2.84 million km^2) in 2030 to 43 % of the continent (3.30 million km^2) in 2100.

Marginal areas became the second majority group in aflatoxin projections of CSIRO-Mk3.0 and MIROC-H models. Both models projected a decrease in these areas. By the end of the projection years, CSIRO-Mk3.0 projected a decrease of 58 and 42% of marginal areas, based on SRES A2 and SRES A1B scenarios. In 2030, marginal areas based on SRES A2 and A1B are projected to be 38 and 37% of the Australian continent (2.92 and 2.84 million km^2); while in 2100, they are projected to be 16 and 22% of the Australian continent (1.23 and 1.69 million km^2). Similarly, MIROC-H also projected a decrease of 30 and 23% of marginal areas based on SRES A2 and SRES A1B scenarios, respectively. In 2030, both scenarios projected 43% of the Australian continent (3.30 million km^2) to be marginal areas; while in 2100, the marginal areas of SRES A2 and

SRES A1B are projected to be 30 and 33% of the Australian continent (2.30 and 2.53 million km^2), respectively.

Only a small portion of the Australian continent will be optimal and suitable for aflatoxin persistence under two climate model projections. Based on SRES A2 and SRES A1B scenarios, CSIRO-Mk3.0 suggests that less than 10% of the continent (0.76 million km^2) will be in these categories, with a decrease throughout the projection years. Between 2030 and 2100, it is expected that optimal and suitable areas of SRES A2 CSIRO-Mk3.0 projections decrease up to 43 and 33%, respectively. Meanwhile, SRES A1B scenario shows smaller reduction, i.e. 33 and 35%, for optimal and suitable areas, respectively. On the other hand, MIROC-H projections show an increase of optimal and suitable areas throughout the projection years. In 2030, 10% of the Australian continent (0.76 million km^2) is projected for each of these areas based on SRES A2 and SRES A1 scenarios. However, in 2100, the optimal and suitable areas of SRES A2 scenario are projected to become 12 and 15% of the Australian continent (0.92 and 1.15 million km^2), respectively. These projections result in an increase of 20 and 50% of optimal and suitable areas. Slightly different, SRES A1B results depict that 11 and 13% of the Australian continent (0.84 and 0.99 million km^2) will become optimal and suitable areas for aflatoxin invasion in 2100. These correspond to an increase of 11 and 33% of optimal and suitable areas in 2030.

Examining stress projections, both CSIRO-Mk3.0 and MIROC-H projected that some of the temperate climate regions of Australia, i.e. the south-eastern areas, will experience cold stress for aflatoxin persistence in the future. However, the severity and coverage areas of MIROC-H projections are higher than CSIRO-Mk3.0 projections. Nevertheless, both models predicted a reduction in areas of cold stress throughout the projection years. In terms of dry stress, the projections of two climate models are different. The coverage areas and severity of MIROC-H projections remain relatively unchanged from 2030 to 2100. Meanwhile, CSIRO-Mk3.0 projected an increase of dry stress areas and severity throughout the projection years. Dry stress projections of the CSIRO-Mk3.0 model cover almost the entire arid climate zone of Australia, while MIROC-H projections only cover some parts of Australia's arid zone. Looking into heat stress projections, both climate models projected a significant increase of heat stress at the end of the projection years. At the beginning of the projection years, only small areas in the north-western part of Australia experience heat stress. However, at the end of the projection years, heat stress areas have expanded to most of the areas in the northern and central parts of Australia. Comparing the two models, heat stress areas of CSIRO-Mk3.0 are larger than those of MIROC-H.

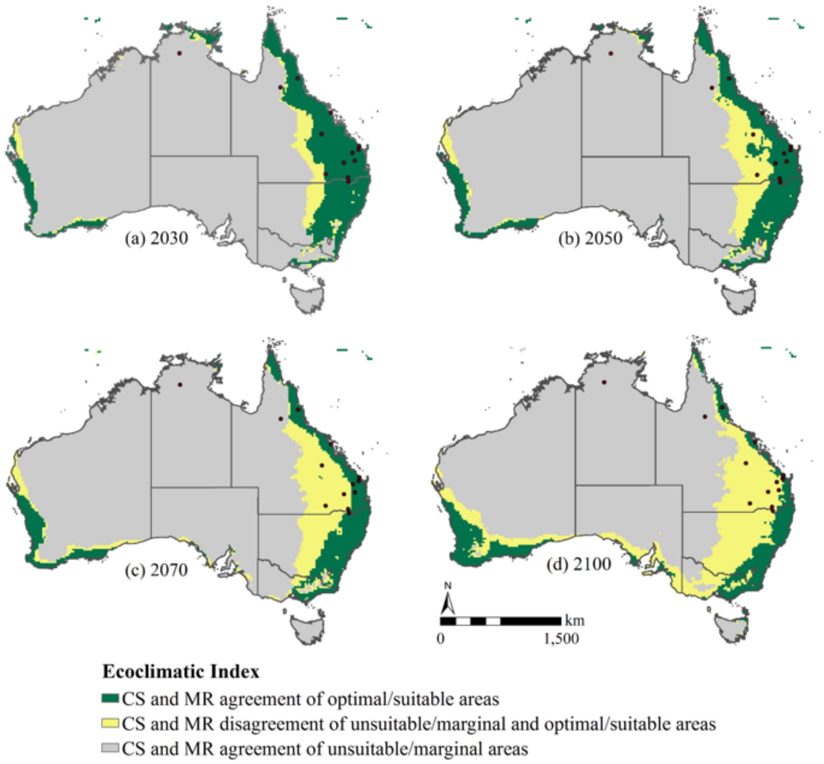


Fig. 11 CSIRO-MK3.0 and MIROC-H overlaid map of aflatoxin projection in Australia using CLIMEX model based on SRES A2. Red dots represent distribution areas of peanut crops

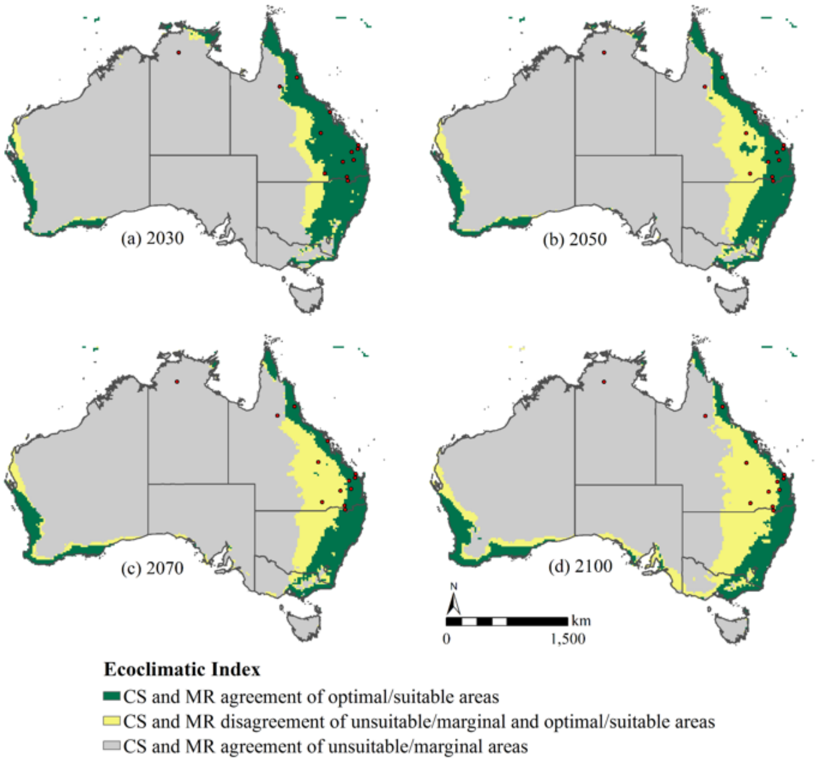


Fig. 12 CSIRO-MK3.0 and MIROC-H overlaid map of aflatoxin projection in Australia using CLIMEX model based on SRES A1B. Red dots represent distribution areas of peanut crops

The overlaid results of future aflatoxin models between CSIRO-Mk3.0 and MIROC-H projections based on SRES A2 and SRES A1B scenarios are presented in Fig. 11 and Fig. 12. In general, the differences in the projections of optimal/suitable areas for aflatoxin persistence from both climate models are noticeable throughout the projection years, i.e. from 2030 to 2100. As a result, the agreement of these areas between the two climate models has reduced significantly at the end of the projection years. In 2030, both climate models agreed that around 15.66 and 15.30% of the Australian continent (1.15 million km^2) will be optimal/suitable for aflatoxin contamination, respectively, based on SRES A2 and SRES A1B scenarios. However, in 2100, this percentage will be reduced to 9.54 and 10.08% (0.69 and 0.76 million km^2). In the earlier projection years (2030 and 2050), the agreement of optimal/suitable areas are mainly located in tropical and subtropical climate zones of the eastern part of Australia. At the end of the projection years (2100), the majority of the agreement of these areas is mainly located in temperate climate zones of the south-eastern and south-western parts of Australia.

Reduction in areas was also observed in the agreement of unsuitable/marginal areas for aflatoxin contamination. In 2030, 79.95 and 79.79% of the Australian continent (6.07 million km^2) were accounted for this category based on SRES A2 and SRES A1B scenarios. However, in 2100, the percentage has decreased to 72.62 and 74.96% (5.53 and 5.69 million km^2). Meanwhile, the areas of disagreement between CSIRO-Mk3.0 and MIROC-H in determining the suitability areas for aflatoxin infection has increased from 4.40% (SRES A2) and 4.91% (SRES A1B) in 2030 to 17.84% (SRES A2) and 14.96% (SRES A1B) in 2100. In 2030, both climate models agree that most of the subtropical region in the eastern part of Australia is predicted to be optimal/suitable, while in 2100, both climate models disagree on the suitability of aflatoxin infection in this region.

4. Discussion

4.1.Aflatoxin distribution under the current climate

The CLIMEX model of aflatoxin developed in this study has high reliability. It shows a strong agreement between distribution areas used for the CLIMEX fitting process, i.e. the African and American continents, and distribution areas used for model validation, i.e. India, China, the Philippines, Thailand, Indonesia, Italy, and Australia. In addition, the inclusion of all aflatoxin distribution data into the CLIMEX model and the fact that most of the distribution data were categorised as optimal areas for aflatoxin infection, confirms the model's reliability and applicability in all parts of the world.

The model shows that majority of optimal areas for aflatoxin contamination are located in the tropical and subtropical climate regions, such as South East Asia, Central

America, the central part of Africa, India, the USA, Brazil, and Argentina. Only a small number of aflatoxin distributions from these climate regions was categorised as suitable and marginal areas for aflatoxin contamination. Therefore, these results confirmed the susceptibility of tropical and subtropical climate zones for aflatoxin contamination, as previously cited by other researcher such as Pettit and Taber (1968). The tropical climate is characterised by a minimum temperature of ≥18°C and minimum precipitation of around 60mm. Meanwhile, subtropical climate zones of warm temperate humid and winter dry are characterised with minimum temperatures between 3 and 18°C, and maximum temperatures of ≥ 22°C during summer time (Kottek et al. 2006). Since aflatoxin infection occurs in these climate ranges, the climate zones provide environmental factors favourable for the infection.

As aflatoxin production in peanut is determined by environmental factors, namely temperature, relative humidity, and moisture content of the peanut substrate (Pettit and Taber 1968), extreme heat and elongated drought stress in the final four to six weeks of the peanut growth period will stimulate pre-harvest aflatoxin contamination in peanut crops (Chauhan et al. 2010). Heat and drought stresses can affect plant physiology, which in turn can increase crop susceptibility for aflatoxin infection (Klich 2007). For example, the formation of phytoalexins, i.e. antimicrobial compounds used to prevent aflatoxin infection, is repressed during drought stress (Klich 2007). In addition, drought stress incidence increases the production of proline in crops (Barnett and Naylor 1966), which is known as a stimulus agent for aflatoxin production (Payne and Hagler 1983). Another factor that supports aflatoxin contamination is the ability of *Aspergillus* species, especially *A. flavus* to persist in high temperature conditions (i.e. up to 40°C) where other fungi cannot persist; providing a competitive advantage for *Aspergillus* species (Klich 2007).

4.2.Aflatoxin distribution under future climate scenarios

It is important to be knowledge-based instead of product-based in anticipating the impacts of climate change and in developing mitigation and adaptation strategies (Sutherst 2003). The modelling technique used in this study provides the likely distribution of aflatoxin occurrence in the event of climate change. Moreover, the model uses a geostatistical approach which projects the response in the form of spatial structure, and thus enables the location of hotspot areas easily. The results of this study indicate a geographical distribution shift of aflatoxin occupation areas in Australia in the future, due to the impact of climate change. Understanding this issue will help to improve aflatoxin management in Australia, as knowledge of projected aflatoxin outbreaks will enable the preparation and implementation of countermeasures in mitigating the negative effects of aflatoxin.

Climate change influences the components of complex biological interactions differently (Newton et al. 2011). Although many factors, such as biological issues (e.g. susceptible crop and compatible toxigenic fungus) and harvesting conditions (e.g. crop maturity, temperature, moisture, and detection/diversion) can generate aflatoxin contamination, climate factors remain the most important (Paterson and Lima 2010). Climatic conditions alter the complex communities of aflatoxin-producing fungi (*aspergillus*), for example modifying the fungi number and fungal community structure (Cotty and Jaime-Garcia 2007).

This study confirms the impact of climate change in the distribution of aflatoxin in peanut crops. It reveals that most of the Australian continent will not be suitable for aflatoxin persistence in the future. The increase of areas suffering from severe dry and heat stresses leads to the increase of unsuitable aflatoxin areas as projected by climate models and scenarios used in this study. The temperate region of the south-eastern part of Australia is projected to become more tolerant for aflatoxin contamination in the future, due to the warmer temperature. This result is consistent with the first outbreak of aflatoxin in 2003-2004 in areas known as free zones of aflatoxin infection due to the alteration of hot and dry climate (Perrone et al. 2014). There is a risk of shifting away from traditional aflatoxin areas due to the increase of average temperature, particularly shifting the aflatoxin areas into cool and temperate climate regions, such as South East Europe (Paterson and Lima 2010; Perrone et al. 2014).

The possibility of aflatoxin incidence in temperate regions should be anticipated by appropriate adaptation measures. One of these is relocation of peanut cropping areas. However, the challenges are enormous, for example farmers' reluctance to move, climate suitability, competition from other commodities, and availability of infrastructures or facilities (e.g. irrigation, transportation, and storage facilities) (Hillel and Rosenzweig 2013). Relocation is a strategic decision which needs to be managed carefully in terms of addressing many factors involved. To be successful, support from government and community is important (Hillel and Rosenzweig 2013). In terms of farmers' capacity to adapt, Marshall et al. (2014) pointed out the need of farmers to expand their networks, enhance their employability, build their strategic thinking and planning capabilities, plan for business profitability, acquire local knowledge, build environmental awareness, employ irrigation, and utilize climate technology. One example of relocation is the establishment of peanut farming in Katherine, the Northern Territory, Australia due to production reduction and aflatoxin persistence in the traditional peanut growing region of the South Burnett, Queensland, Australia. However, this strategy was later abandoned due to financial difficulties, problems in developing intensive cropping system, and projected unsuitability of future climate (Hillel and Rosenzweig 2013; Marshall et al. 2014). This failure provides an illustration of the risk inherent with adaptation strategies of relocation.

The overlaid aflatoxin maps resulting from CSIRO-Mk3.0 and MIROC-H climate models were produced to observe the common areas for aflatoxin suitability, as conducted by Shabani and Kotey (2015) in projecting the future distribution of cotton (*Gossypium*) and wheat (*Triticum aestivum* L) in Australia. This method will confirm the reliability of suitable areas of aflatoxin occurrence in Australia, and will thus minimise possible errors in using the results of this study. The differences in the results between these two climate models are expected, since each model employed different methods in quantifying the effects of climate change in the future. The CSIRO-Mk3.0 model however was developed by an Australian research institute (CSIRO) and therefore could include more specific information about Australia.

As most of the Australian continent is projected to be not suitable for aflatoxin invasion, it can be said that the risk of aflatoxin infection is quite small. However, this is not the case. The unsuitable areas are located in the arid climate regions of Australia, which are not appropriate for agricultural practices, including the cultivation of peanut crops. Unfortunately, both CSIRO-Mk3.0 and MIROC-H models have projected that current peanut cultivation areas are at risk of aflatoxin invasion by 2030. Although the two models reveal different results by the end of the projection years, aflatoxin risk is still apparent for peanut crops in Australia. Thus, it can be inferred that current peanut growing areas are under aflatoxin risk in the future. Consequently, apart from the relocation strategies explained above, prevention and mitigation strategies should be developed and maintained as a way of anticipating this risk.

Several methods have been developed in the prevention and mitigation measures of aflatoxin invasion in peanut crops. The major prevention program is the development of host-plant resistance, which was initiated in the late 1960s and is ongoing (Torres et al. 2014). The challenges of this program are the lack of resistance genes, and the development of resistance crops under all conditions (Kumar et al. 2017; Torres et al. 2014). Another important prevention measure is conducting appropriate agricultural practices, which consist of crop rotation, proper planting date, optimal plant densities, irrigation, and fertilization (Torres et al. 2014). Meanwhile, for contaminated crops, the effective mitigation measures includes physical, chemical, and biological approaches (Baranyi et al. 2015; Kumar et al. 2017).

5. Conclusion

This study has successfully developed CLIMEX model parameters for aflatoxin. The consistency of the results between aflatoxin map produced from the CLIMEX model and the aflatoxin geographical distribution map has ensured model reliability. The results support the outcomes of other studies which confirmed the climatic zone preferences of aflatoxin incidence. The future projections of aflatoxin distribution in Australia under CSIRO-Mk3.0 and MIROC-H GCMs based on SRES A2 and SRES A1B indicated that only a small portion of the Australian continent will be optimal/suitable for aflatoxin persistence, due to the incidence of heat and dry stresses. Unfortunately, the majority of current peanut growing areas are projected to be optimal/suitable for infection. This study also confirms shifts in aflatoxin invasion areas from the tropical and subtropical climate zones of the eastern part of Australia to the temperate climate zones of the south-eastern and the south-western parts of Australia by 2100. Thus, it supports the findings from previous works conducted in other parts of the world. Having all of this key information will provide valuable resources in developing adaptation and mitigation response in managing the incidence of aflatoxin in the future. Among the adaptation and mitigation measures are relocation of planting areas, development of host-plant resistance, proper agricultural practices, and mitigation actions by using physical, chemical, and biological approaches. Finally, this study is based on the suitability of climatic conditions, thus further analysis is needed to include other factors of aflatoxin invasion, such as host availability, susceptibility and abundance, historical contingency (e.g. evolutionary change) and interacting factors, such as crop and pest management, crop rotation, and crop acreage.

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