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A Spatio–Temporal investigation of risk factors for aflatoxin contamination of corn in southern Georgia, USA using geostatistical methods

Ruth Kerry [a, *], Brenda V. Ortiz [b], Ben R. Ingram [c], Brian T. Scully [d]

[a] Department of Geography, Brigham Young University, UT, USA
[b] Crop, Soil, and Environmental Sciences Department Auburn University, AL, USA
[c] Facultad de Ingeniería, and Research Program on Adaptation of Agriculture to Climate Change (A2C2), Universidad de Talca, Curicó, Chile
[d] USDA-ARS, U.S. Horticultural Research Laboratory, Ft. Pierce, FL, USA

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ABSTRACT

Aflatoxin is a mycotoxin produced by the *Aspergillus flavus* fungi that can severely contaminate corn grain. The U.S. Food and Drug Administration (FDA) have set a limit of 20 ppb, total aflatoxin, for interstate commerce of food and feed as it can induce liver cancer in humans and animals. Contamination is exacerbated by high temperatures, drought conditions and light-textured soil which are all common in Georgia (GA). Lack of irrigation infrastructure can further amplify drought stress and aflatoxin contamination. Accurate aflatoxin assessment requires the collection of multiple corn samples, is expensive and conducted at harvest which does not allow for the use of in-season mitigation strategies to reduce the risk. Given the expense of measurement and the consequences of crop loss, an important goal for agricultural extension services is the prediction and identification of years and counties at higher risk of aflatoxin contamination. This would allow growers to deploy management tactics to reduce risk and to reduce unnecessary expense on aflatoxin testing. In this research, aflatoxin levels were analysed by Poisson kriging and used to validate a strategy for identifying high risk years and counties. It is based on mapping risk factors (Maximum June temperatures, June rainfall, % corn planted area and % soil drainage types) that are above key thresholds. The aflatoxin data used were county level, collected unevenly in space and time from 1977 to 2004 in 53 counties in southern GA. Averaging and typical geostatistical methods were unreliable for producing a temporal summary of the spatial patterns because aflatoxin data were highly skewed and approached a Poisson distribution, and averages for counties with fewer observations are less reliable. Poisson kriging down-weights the influence of these in variogram computation and the estimation process. Comparison tests confirmed significant differences in aflatoxin levels between counties and years that were identified as having different levels of risk using the risk factors approach. Sensitivity analysis for Poisson kriged aflatoxin risk showed that the more years of data are clearly better for this analysis, but fewer than 15 years of data were not advisable.

1. Introduction

Aflatoxin is a mycotoxin produced by fungi (*Aspergillus flavus* or *Aspergillus parasiticus*) which can contaminate several staple crops such as peanut, (Brenneman et al., 1993), millet (Wang et al., 2010; Wilson et al., 1993), rice (Abbas et al., 2005), sorghum (Adegoke et al., 1994), wheat (Patriarca et al., 2014) and corn (Payne, 1992). Aflatoxin can cause liver cancer in humans and animals (Barrett, 2005; FDA, 2012). The Food and Drug administration office (FDA) of the USA have set a limit of 20 ppb, total aflatoxin, to restrict use of corn, peanut products, cottonseed meal, and other animal feeds and feed ingredients intended for dairy animals, for animal species or intended for immature animals. There is also a limit of 100 ppb restricting use of corn and peanut products intended for breeding beef cattle, swine, or mature poultry (FDA, 2015). Infection of corn with *A. flavus* or *A. parasiticus* is exacerbated by high temperatures, drought and high net evaporation (Guo et al., 2008; Horn et al., 2014; Payne, 1992) associated with particular climatic areas

* Corresponding author.
E-mail address: ruth_kerry@byu.edu (R. Kerry).

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(Abbas et al., 2007; Patriarca et al., 2014), agro-ecological zones (Setamou et al., 1997) and soil types (Palumbo et al., 2010). Statistically, there are 16–31 times more deaths from liver cancer in less developed countries due at least in part to aflatoxin contamination of food (Liu and Wu, 2010) and many of these countries are predominantly hot and often drought prone (Wu and Khlangwiset, 2010). Several studies have examined possible increased contamination rates under climate change scenarios (Medina et al., 2014 and Medina et al., 2015) and suggest that aflatoxin contamination will increase in many areas as temperatures rise.

In Georgia (GA) and throughout the southern USA, corn is planted as a summer crop and is highly susceptible to aflatoxin contamination (Widstrom et al., 1996). Rainfall variability and high temperatures in this region during summer, along with light textured soils that exacerbate drought or water stress, all influence contamination. Also, lack of irrigation infrastructure in some areas can further aggravate water stress (Brenneman et al., 1993). Salvacion et al. (2011) found that June maximum temperatures and precipitation were key predictors of aflatoxin contamination in southern Georgia (GA), USA. Damianidis et al. (2015) found that the risk of aflatoxin contamination changes specifically with corn hybrid planted, soil type and the weather conditions before and after the mid-silk growth stage, which usually occurs in June across the Southeast US. Using the drought index, ARID, as an aflatoxin risk predictor, they also found that a 0.1 increase of in-field drought, as quantified by ARID, during key weeks before and after mid-silk, increased the probability of aflatoxin contamination over the FDA threshold of 20 ppb.

Accurate aflatoxin assessment usually requires the collection of multiple grain samples. There are several methods available but most are time-consuming and expensive (Papadoyannis, 1990) and conducted at harvest which does not allow implementation of in-season management practices to reduce risk. Given the expense of aflatoxin measurement, an important goal for agricultural extension services and crop consultants would be the ability to identify those years and counties most at risk of contamination to reduce unnecessary expense on testing in years and areas when there is little risk of contamination. Identification and prediction of years and counties at risk would allow the implementation of management strategies such as irrigation in season to reduce contamination risk and the use of resistant varieties (Chen et al., 2002, 2006; Guo et al., 2011; Menkir et al., 2008). Another goal of agricultural extension services could be to provide an easy to use, computationally efficient, online decision support tool to assess aflatoxin contamination risk that could work for large datasets. Crop consultants would also require a simple approach to determining risk that could be executed in commercially available, user-friendly software.

The purpose of this research was to apply geostatistical methods to develop a predictive tool using a risk factors approach for identifying problematic years and counties with a longer term view to being able to implement the tool as part of an online decision support system. To validate the risk factors approach, a space-time summary of aflatoxin risk is needed. Similar to soil contaminants, aflatoxin data, as a crop toxin, can be expected to be highly skewed. In soil contamination studies, indicator kriging (Goovaerts, 2009) has been used to map the risk of exceeding a particular contamination threshold (Goovaerts et al., 1997). Indicator kriging, however, requires sufficient data to compute a reliable variogram for each year and would result in a risk map for each year with no practical way to produce a space-time risk summary. Aflatoxin data collected from regional sampling is often skewed and approaches a Poisson distribution. Practitioners often analyze data that has been collected by third parties who have not considered potential geostatistical investigations. Many times, such data have also been collected irregularly in space and time. The 27 year Georgia aflatoxin survey appears to fit these criteria, and these data are perhaps better understood using Poisson kriging. Poisson kriging was first developed by Monestiez et al. (2006) to investigate rare whale sightings, which tend to have a Poisson distribution, and had been observed irregularly in space and time. Poisson kriging has been further adapted for use with sightings of other rare animals (Kerry et al., 2013), used in studies of mortality rates from rare diseases (Goovaerts, 2005, 2006a,b) and the investigation of crime rates (Kerry et al., 2010). Poisson (Goovaerts, 2006a,b) and Binomial kriging (Oliver et al., 1998) have been used interchangeably in the literature for mapping rates of rare disease and although superficially different, often lead to similar results (Flanders and Kleinbaum., 1995). Even though Binomial kriging may be more theoretically appropriate in certain cases where the characteristics of the data are known *a priori*, it adds an extra layer of complexity requiring an additional parameter in computations. Indeed, as the number of trials increases, the Binomial distribution approaches the Poisson distribution (Haining et al., 2010) and its use can be justified here since assumptions about the prevalence of aflatoxin are avoided. Furthermore implementations of Binomial kriging are not available in user-friendly, commercially available software packages. Spatially irregular observations or the analysis of rate or proportion data can suffer from the "small number problem" (Haining et al., 2010) and be unreliable in areas that have received less sampling effort or are sparsely populated. For example, if a given county was only sampled in a particularly high risk year but other counties were sampled over several years, the county with just one measurement would seem to have very high aflatoxin levels. Binomial or Poisson kriging can be used to give a space-time summary of aflatoxin contamination data collected over a 27 year period (1977–2004) in 53 counties in southern GA that takes account of the "small number problem", but here the latter will be used due to computational simplicity with a view to the eventual implementation in an online decision support tool or use by agricultural consultants using commercially available software. Due to irregular sampling in space and time there are insufficient data to employ other geostatistical methods for individual years. The space-time summary of aflatoxin contamination in southern GA produced by Poisson kriging will be used to assess the viability of a risk factors approach for identifying the counties and years at greatest risk of aflatoxin contamination. Based on existing literature, several key risk factors namely Maximum June temperatures (June TMax) (Salvacion et al., 2011), June Rainfall (June RF) (Salvacion et al., 2011; Damianidis et al., 2015; Windham et al., 2009), amount of corn grown and proportion of droughty soil types (Damianidis et al., 2015) are examined and key thresholds related to aflatoxin contamination identified. Another secondary aim of this research is to conduct a sensitivity analysis of the number of years of data used to create a Poisson kriged space-time summary of risk.

2. Methods

2.1. Data collection

Between 1977 and 2004, corn grain samples were collected at harvest to measure aflatoxin content at the county level. Samples were collected using a grab sampling technique where 10 ears were collected for each sampling and there was an average of 3 replications per county. The study area was 53 counties in southern GA (Fig. 1A). Aflatoxin levels in ppb were measured by the USDA-ARS Crop Protection and Management Research Unit and the University of Georgia, Natural Products Laboratory in Tifton, GA. Aflatoxin levels were not measured in every county in every year. Data were