Monitoring peanut contamination in Mali (Africa) using the AVHRR satellite data and a crop simulation model

Vijendra K. Boken[1]*, Gerrit Hoogenboom[1], Jonathan H. (Tim) Williams[2], Bamory Diarra[3], Siriba Dione[3], and Gregory L. Easson[4]

[1.]Department of Biological and Agricultural Engineering, The University of Georgia, Griffin, GA 30223, USA; [2.] Peanut-Cooperative Research Support Program (CRSP), University of Georgia, Griffin, GA 30223; [3.] l'Institute d'Economie Rurale, Bamako, Mali.

*Corresponding author's address: Department of Geography and Earth Science, University of Nebraska at Kearney, Kearney, NE 68849, USA.

Abstract

Peanut is the main legume crop of Mali, West Africa. It can be contaminated by aflatoxin, a natural toxin that may develop due to drought conditions at pre-harvest stage and also due to temperature- and humidity-related factors that may occur during the post-harvest storage. Consumption of aflatoxin-contaminated peanut can cause liver diseases, such as jaundice, hepatitis, or cancer. In this paper, we present a case study for Mali, West Africa, and identify weather and satellite based variables that could be used to indicate aflatoxin presence in peanut. Based on such monitoring and predicting, a warning may be issued against eating contaminated peanuts to keep the public health from deteriorating. The Normalized Difference Vegetation Index (NDVI) composites, that were derived from the Advanced Very High Resolution Radiometer (AVHRR) satellite data, were averaged for the reproductive phase of peanut and were examined for their relationship with the annual peanut yield, an indicator of drought and aflatoxin. The relationship was found to be moderate ($R^2 = 0.56$). The commencement and termination dates for the reproductive phase of peanut were determined by using a crop simulation model. Aflatoxin amounts were measured for peanut samples collected from various locations across Mali and were found to be linked to the NDVI, total precipitation, and maximum temperature averaged over the reproductive phase of peanut.

Keywords: Aflatoxin, georeferencing DSSAT, NDVI, yield prediction.

1. Introduction

Aflatoxin is a natural toxin that can contaminate various food crops (for example, peanut, maize, sorghum, and wheat) due to the growth of a fungus called *Aspergilus flavus*. People who consume food grains contaminated by aflatoxin are reported to have developed liver diseases,

such as jaundice, hepatitis B, or cancer (Wild et al. 1993, Key et al. 2004). Between January and June of 2004, 125 deaths were reported in eastern and central provinces of Kenya due to the consumption of aflatoxin-contaminated maize that led to an outbreak of jaundice (CDC 2004). If aflatoxin can be predicted around harvest time, it would be possible to warn the national and local governments and the general public against eating contaminated food grains. As an alternative, supplemental food grains could be made available by the governmental, non-governmental, or international agencies to keep public health from deteriorating. In this paper, we attempt to identify the AVHRR and weather data based variables that could be used to monitor or predict aflatoxin in peanut (*Arachis hypogaea* L.). Using the potential indicators of aflatoxin, an international agency could develop an aflatoxin early warning system for Africa. This study is only a preliminary step toward achieving that goal.

1.1 Study Area and Objectives

We present a case study for Mali in West Africa, where agriculture is the main economic activity and contributes to about half the national gross domestic product (GDP). Most of the agriculture in Mali is practiced in its southern part, because the northern area falls within the sub-Saharan region and is unsuitable for agriculture. Peanut is the most important legume crop of Mali and is mainly grown in five of its provinces (Kayes, Koulikoro, Sikasso, Segou, and Mopti; Figure 1). Most of the peanut crop in Mali is characterized as rainfed; that means its water requirement is met primarily by rainfall. Peanut is usually sown during May-June when the rainy season begins and is harvested in September-October.
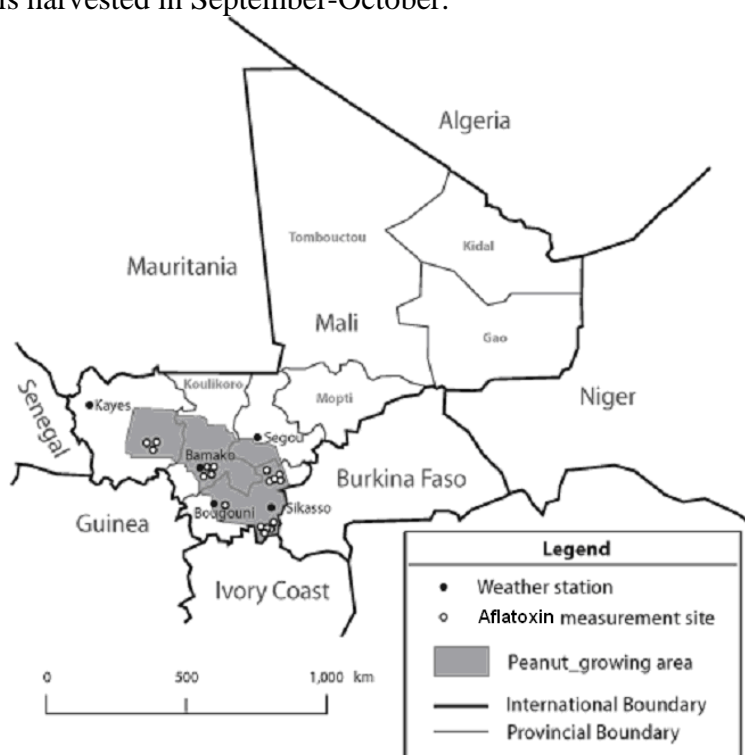

Figure 1. Map of Mali showing the peanut growing area, aflatoxin sites, and the locations of weather stations.

There are frequent observations of peanut contamination in Mali. However, the Malian Government does not have any systematic plan to monitor aflatoxin on a regular basis. Whenever there are reports of aflatoxin contamination, a limited number of peanut samples are collected for aflatoxin measurements. Hence the current practice of aflatoxin monitoring in Mali is not effective and needs improvement. In the present study, an attempt is made to improve aflatoxin monitoring by using satellite data. Although there are no concrete plans at present to use satellite data by a governmental agency in Mali, satellite data are consistently used by international agencies, such as Famine Early Warning System (www.fews.net) to monitor crop health conditions in Africa. The specific objectives of this study are: i) to monitor peanut yield using a crop simulation model and the AVHRR satellite data, and ii) to identify weather and AVHRR-based variables that are linked to aflatoxin in peanut.

2. Data Collection

Aflatoxin is likely to develop in peanut under the drought or moisture-deficit conditions (Cole et al. 1989, Sanders et al. 1993). This aflatoxin-drought link is also supported by Sinha and Sinha (1991) who collected 416 samples of various food grains in India during 1987-1989. Out of the 416 samples, 162 were found to be aflatoxin positive. The maximum amount of Aflatoxin was found in the samples collected in 1987, which was one of the worst drought years recorded for India (Rao and Boken 2005). Considering the drought-aflatoxin link, we focused on the weather and satellite data that are capable of effectively monitoring drought conditions over large areas and collected the AVHRR satellite data, daily weather observations, peanut yield, and aflatoxin data for the peanut-growing region in Mali.

2.1 AVHRR Satellite Data

The AVHRR data are available in five spectral channnels with daily temporal resolution, a spatial resolution of about 1 km, and a very wide swath width. Due to these characteristics, the AVHRR data have been used for monitoring vegetation conditions over large areas (Tucker et. al 1984, Goward et al. 1991, Gutman 1991, Weigant et al 1991, Williams and Jenlinski 1996, Boken and Shaykewich 2002, Kogan 2002, and Knudby 2004). In particular, two of the AVHRR channels, in red and infrared ranges, have been used to generate various vegetation indices for monitoring vegetation effectively. Out of the various vegetation indices, some of which are described in Anyamba et al. (2005), the NDVI proposed by Rouse et al. (1974) has been most widely used for monitoring crop conditions in African and other countries. NDVI is expressed as the ratio of the difference to the sum of the pixel values in the visible and near-infrared wavelengths.

Rasmussen (1997) estimated pre-harvest yield for pearl millet in Senegal using NDVI data integrated over the reproductive period and found a strong correlation ($R^2 = 0.72$) between peanut yield and the integrated NDVI. NDVI was modeled as a function of time and then integrated between time limits corresponding to commencement and termination of the reproductive phase. Lewis et al. (1998) used NDVI for estimating maize yield for 36 agricultural district of Kenya for the 1982-90 period.

Sannier et al. (1998) found that 10-day composites of NDVI were significantly correlated with maize production in the main agricultural region of Zambia. Using other AVHRR based indices,

Vegetation Condition Index and Temperature Condition Index, Unganiai and Kogan (1998) monitored drought conditions by estimating maize yield for South Africa.

In recent years, realizing the potential of AVHRR data for vegetation monitoring over large areas, the National Aeronautics and Space Administration (NASA) has generated NDVI data sets, with 8 km resolution, for different regions of the world (Tucker et al. 2005). These datasets were generated under a Global Invetory Monitoing and Modeling Studies (GIMMS) project. For the African continent, the 10-day (dekadal) composites of NDVI images are available from the Africa Data Dissemination Service (2005). These composites were generated to minimize the cloud coverage. We downloaded the dekadal NDVI-GIMMS data for Africa for the period from 1985 to 2000 and extracted data for the desired region using a geographic information system as discussed in the methodology section.

2.2 Weather Data
We obtained the daily observations for maximum temperature (T_{max}), minimum temperature (T_{min}), precipitation (P), and sunshine hours for five weather stations (Bamako, Bougouni, Kayes, Segou, and Sikasso; Figure 1) from the Direction National de la Meteorologie of Mali for the period from 1985 to 2000. The weather stations were within or close to the peanut growing region.

2.3 Peanut Yield Data
The AGRHYMET Regional Center has compiled agricultural, hydrological, and meteorological (i.e., AGRHYMET) data for a few countries in sub-Saharan regions (AGRHYMET, 2002). We obtained data pertaining to the yield and the harvested area of peanut from the AGRHYMET Centre. While the national level data were available for the 1985-2000 period, the provincial level data were available only for 1985-1987, 1989-1993, and 1999. No data were available at county or district levels.

2.4 Aflatoxin Measurements
Peanut samples were collected in 1999 from different locations across the peanut growing region of Mali. The aflatoxin amount was measured for these samples using the Enzyme-Linked Immunosorbent Assay (ELISA) test and was found to range from 4.5 to 12.1 ppb. This range may be considered moderate yet unacceptable considering the policy of zero-tolerance of aflatoxin already enforced in many countries.

3. Methodology

3.1. Georeferencing and Averaging of NDVI Data
The AVHRR-derived NDVI data at the dekadal level pertained to the entire African continent and were not georeferenced. We geo-referenced these NDVI images using the 'Georeferencing' module of the ArcGIS v8.2 software (Environmental Systems Research Institute, Redlands, CA). Using the 'Spatial Analyst' module of the ArcGIS, we then averaged the NDVI values within the peanut-growing region for each dekad throughout the growing period (May through October) for every year from 1985 to 2000. This was done to determine if the NDVI, during the crop growing period, could be used as an indicator of the existence of aflatoxin in peanut. To enhance the contribution of NDVI data to vegetation monitoring, a crop simulation model was used.

3.2 Crop Simulation Model

Various phenological stages, including emergence, leaf development, flowering, grain-filling, ripening, and maturity, occur in a sequence during a crop growing period. These stages may be grouped into two main phases: vegetative and reproductive. The weather conditions during the grain-filling period can significantly affect both crop yield and crop quality. Therefore, the NDVI composites for the reproductive phase are likely to contribute significantly to determining the peanut quantity which may be indirectly related to quality. As stated earlier, droughts can reducte peanut yield (or quantity) and may also deteriorate peanut quality due to aflatoxin-contamination. The problem, however, is that the dates for commencement and termination of a reproductive phase are often unknown and are likely to shift each year, depending on the sowing dates and weather conditions (Kumar 1998). Hence, the researchers attempt to use approximated Julian dates to define the length of a reproductive phase and then select the dates for acquiring satellite data. Unfortunately this is not an accurate approach, because the process of crop development follows a weather-linked crop calendar that is not fixed to the Julian calendar. Any random approximation of the above mentioned dates may result in an error in identifying the reproductive phase and hence diminish the potential of satellite data to crop or vegetation monitoring. A scientifically sound approach is required to determine the duration of a reproductive phase to maximize the potential of satellite data.

We used a crop simulation model to estimate the duration of the reproductive phase of peanut. A crop simulation model simulates crop growth and yield based on genetic data, crop management, local weather and soil data. Various crop simulation models are available in the literature, for example, the Decision Support System for Agrotechnology Transfer or DSSAT (Tsuji et al. 1998, Hoogenboom et. al. 1999, 2004), Environment Policy Integrated Climate or EPIC model (Williams et al. 1989), Agricultural Production System Simulation or APSIM model (APSIM 2006), and biometeorological time scale models (Robertson 1968, Boken and Shaykewich 2002). In this study, we used CSM-CROPGRO-Peanut model, which is part of the DSSAT Version.4 software (Hoogenboom et al. 2004), to determine the dates for commencement and termination of the reproductive phase of peanut. The input data required for this model were crop data (e.g., genetic coefficients), crop management data (e.g., sowing date, soil type, row spacing, and fertilizer application) and weather data (daily maximum and minimum temperatures, precipitation, and sunshine hours).

The genetic coefficients were provided by K. J. Boote of Agronomy Department, University of Florida. We estimated the sowing dates during May-June by examining daily rainfall records. It was assumed that a farmer will sow peanut if the total rainfall in two consecutive days during May-June exceeded 20 mm. Soil information was obtained from the FAO soil map (http://www.fao.org/WAICENT/FAOINFO/AGRICULT/agl/agll/dsmw.HTM. Row spacing was assumed to be 20 cm and a nominal amount of fertilizer (50 Kg N per ha) was also assumed based on the information available locally.

4. Results and Discussion

4.1 NDVI versus Peanut Yield

It is considered that aflatoxin is more likely to develop under drought conditions, that is, when crop yields are less than the average crop yield. We conjecture the aflatoxin/drought link to be primarily due to moisture-deficits during the reproductive phase of the crop (Sanders et al. 1993, Cole et al. 1989). To examine the relationship between the annual peanut yield and the NDVI, the average NDVI during crop growing period has been found to be a significant variable affecting crop yield (Boken and Shaykewich 2002, Knudby 2004). We determined the commencement and termination dates for reproductive phase of peanut using the DSSAT program, for the years when annual peanut yield (total production per unit of harvested area) data were available (i.e., 1985-1987, 1989-1993, and 1999; Table 1).

Table 1. The commencement and termination dates (month/day) of the reproductive phase of peanut as estimated by the DSSAT program.

Site	1985	1986	1987	1989	1990	1991	1992	1993	1999
Bamako	7/5 – 9/21	7/2 - 9/17	6/5 - 10/6	6/27-9/12	7/8 - 9/24	7/2 - 9/17	7/27 - 9/12	6/15 - 9/1	7/10 - 9/23
Segou	7/14 - 9/28	7/3 - 9/18	6/17 - 9/3	7/17-10/2	7/3 - 9/18	7/9 - 9/24	7/2 - 9/17	6/13 - 9/12	6/30 - 9/13
Kayes	6/18 - 9/4	6/20 - 9/7	7/18 - 10/2	7/24-10/8	7/14 -9/26	7/12 - 9/26	7/6 - 9/19	7/1 - 9/16	7/26 - 10/10
Bougouni	6/24 - 9/10	6/11 - 8/27	6/26 - 9/10	6/14-8/30	6/11 -8/27	6/15 - 8/30	6/12 - 8/28	6/30 - 9/16	6/19 - 9/2
Sikasso	6/29 - 9/16	6/12 - 9/28	6/19 - 9/4	6/13-8/30	6/12 -8/28	6/19 - 9/3	6/8 - 8/24	6/11 - 8/27	6/11 - 9/27
Average period[1]	7/6 - 9/15	7/22 - 9/13	7/23 - 9/17	6/26-9/16	6/28 - 9/12	6/28 - 9/12	7/1 - 9/5	6/20 - 9/8	7/3 - 9/21
NDVI-dekads[2]	19 - 26	17 - 25	18 - 26	19 - 26	19 - 25	19 - 25	19 - 25	17 - 25	19 - 26

1. Average period of the reproductive phase, 2. The dekad range corresponding to the reproductive phase; dekad 1 refers to the period from January 1 to January 10.

We then determined the average NDVI for the reproductive phase as explained in section 3.1. In order to investigate, as a first step, if the NDVI was linked to low yields (and hence drought and aflatoxin), a correlation analysis was conducted between the annual peanut yield and the NDVI averaged for the reproductive phase of peanut. The coefficient of determination (R^2) was found to be 0.56 (Fig. 2).
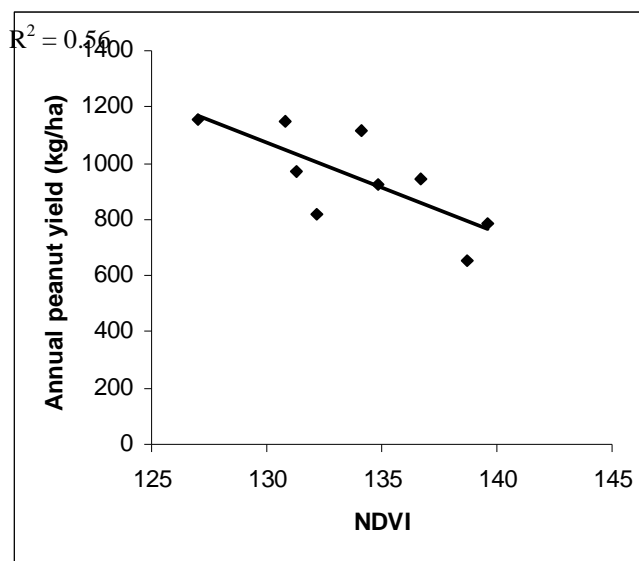
Figure 2. The relationship between the normalized difference vegetation index averaged for the reproductive phase for the peanut-growing region and the annual peanut yield averaged for four provinces (Kayes, Koulikoro, Sikasso, Segou) that account for about 90% of the total peanut area of Mali.

The original range of the NDVI (-1 to +1) had been transformed to 0-255 scale. This moderate level of relationship suggested that the average NDVI during the reproductive phase could be used as a variable that could predict peanut yield and hence drought or aflatoxin. The relationship between yield and NDVI during the reproductive phase was negative. An apparent reason for this negative relationship could be linked to unique processes, different from other crops, that take place during reproductive phase of peanut. The reproductive phase of the peanut experiences yellow flowering which contributes to lowering the average NDVI during the reproductive phase. After the flowers wilt, the pegs enter the ground and the plant energy is partitioned between the vegetative growth during the reproductive phase and the underground fruit development. A higher yield therefore could be expected with lower average NDVI during the reproductive phase. However, it will depend on other complex factors related to peanut variety, such as the proportion of flower-canopy to green-biomass-canopy during the reproductive phase.

4.2 Aflatoxin versus Weather variables
The amount of aflatoxin measured at a post-harvest stage was considered to be a function of the annual peanut yield (an indicator of drought) and weather conditions (precipitation, average T_{max}, average T_{min}, and average sunshine hours) during the reproductive phase of peanut. The aflatoxin amounts measured at 18 representative sites were used for regression against the variables derived from the weather data (Table 2).

Table 2. Data used for the regression analysis between the aflatoxin amount and weather variables

State	Amount of aflatoxin (ppb)	Average during the reproductive phase (11 June – 27 August) in 1999				Peanut yield (kg/ha)
		P (mm)	T_{max} (°C)	T_{min} (°C)	Sunshine hours (hours)	
Kayes	6.8, 9.2, 6.1	486.1	31.8	23.5	6.5	1271
Koulikoro	7.0, 5.0	590.1	30.9	22.4	6.0	963
Sikasso	7.0, 10.0, 5.2, 4.5, 10.0, 9.0, 7.0, 10.0, 5.0, 7.0, 8.8, 12.0, 12.1	712.2	30.1	21.8	6.8	1241

Note: P is precipitation and T_{max} and T_{min} are the maximum and minimum temperatures, averaged for the reproductive phase of peanut.

Finally, 78 datasets were compared using different combinations of aflatoxin measurements (three in Kayes, two in Koulikoro, and 13 in Sikasso i.e., a total of 2x3x13 or 78 datasets) and weather parameters. Regression analyses first were performed between aflatoxin amounts and

the weather variables during the reproductive phase (total precipitation, average T_{max}, average T_{min}, and average sunshine hours). The coefficient of determination, R^2, exceeded 0.50 (ranged from 0.50 to 0.99) for 58% (45 cases out of 78) of the datasets in the case of total precipitation, and 54% (42 cases out of 78) of the datasets in the case of T_{max}. For the remaining variables (peanut yield, T_{min}, and the average sun shine hours during reproductive phase), the percentage of datasets for which R^2 exceeded 0.50 ranged from 38% to 46%. Figure 3 presents examples of the strongest and the weakest relationships thus obtained. Hence, in addition to the NDVI averaged for the reproductive phase, as discussed in the previous section, the total precipitation and T_{max} averaged for the reproductive phase could be used to monitor aflatoxin in peanut.
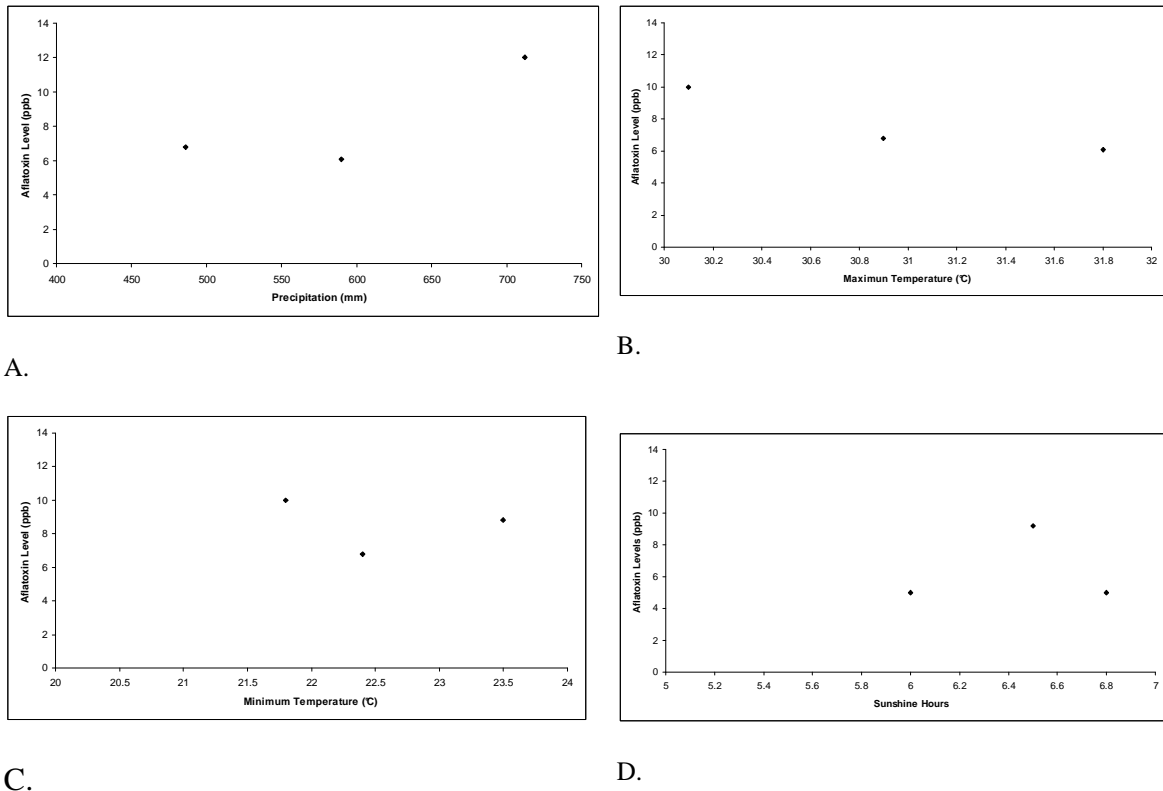

A.

B.

C.

D.

Figure 3. Some examples of the relationships between aflatoxin amounts and weather parameters averaged for the reproductive phase of peanut during 1999; there were 78 cases for each of the parameter.

4.3 Aflatoxin versus NDVI
A direct relationship between aflatoxin and the NDVI at different stages of crop was also examined. The NDVI was averaged for an area encompassing each of the five clusters of the aflatoxin measuring sites (Figure 1 and Table 3).

Table 3. The dekadal Normailized Difference Vegetation Index values, averaged for selected sites, during peanut-growing period in 1999 and the amount of aflatoxin measured after the harvest.

Aflatoxin-site cluster	Aflatoxin amount averaged for the cluster (ppb)	NDVI averaged reproductive phase of peanut and for the area enclosing the aflatoxin-sites cluster, for a dekadal period during 1999									
		July 1-10 (dk19)	July 11-20 (dk20)	July 21-31 (dk21)	Aug. 1-10 (dk22)	Aug. 11-20 (dk23)	Aug. 21-31 (dk24)	Sept. 1-10 (dk25)	Sept. 11-20 (dk26)	Sept. 21-30 (dk27)	Oct. 1-10 (dk28)
Bamako	6.00	75.43	85.90	96.00	106.00	115.70	126.10	131.80	134.70	134.10	130.93
Kayes	7.37	81.96	102.52	115.12	129.18	139.86	151.78	153.21	151.76	145.56	134.67
Segou	7.34	65.60	72.00	79.10	86.80	97.40	104.80	110.30	113.00	112.80	110.40
Sikasso	7.60	108.70	114.90	120.30	125.30	129.90	134.60	139.80	144.50	143.60	140.40
Bougini	10.97	116.40	121.40	123.90	127.40	131.10	141.90	151.30	155.80	155.10	151.20
	R^{2**}	0.56	0.46	0.33	0.20	0.12	0.12	0.21	0.27	0.33	0.39

* dk refers to dekad; dekad 1 is Jan. 1-10 period.

** R^2 is the coefficient of determination obtained from the regression between peanut yield and the NDVI averaged for the area enclosing aflatoxin-sites cluster.

The NDVI images were analyzed using the ArcGIS software. The site clusters were superimposed on an NDVI image and five polygons, each encompassing aflatoxin-site cluster, were created. Using Spatial Analyst module of the software, the NDVI values were averaged for each polygon. This exercise was repeated for all of the NDVI images for 1999 to obtain average NDVI for each cluster (Table 3). Regression analysis was performed to determine at what crop stage the NDVI image exhibited the strongest relationship with aflatoxin amount. As shown in Table 3, the NDVI-aflatoxin relationship was found to be most significant when peanut was at the beginning of its reproductive phase (July1-10). This relationship is presented by Figure 4.
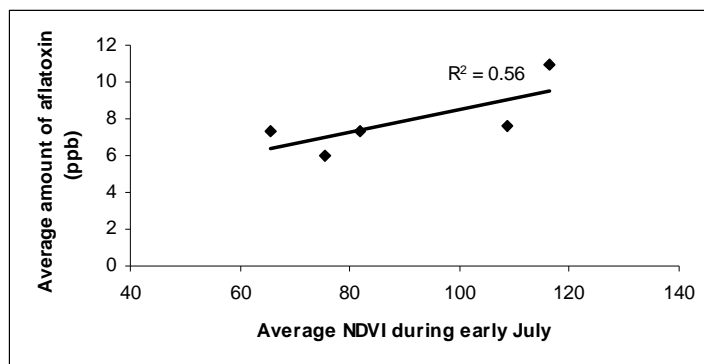

Figure 4. Relationship between the aflatoxin amount and the normalized difference vegetation index (NDVI) averaged for the aflatoxin measuring sites across Mali.

5. Conclusion

A crop simulation model was used to enhance the potential of satellite data for monitoring crop health by estimating the dates of commencement and termination of the reproductive phase of the peanut crop. The AVHRR-based NDVI was moderately linked to peanut yield which could be used to predict drought. Additional studies are required, when yield data are available at district level, to evaluate the relationship between yield and aflatoxin. Nevertheless, a moderate relationship was found between the aflatoxin amounts and NDVI averaged for the first ten days in July i.e., early part of the reproductive phase. In addition, total precipitation and average maximum temperature during the reproductive phase were found to be linked to the post-harvest amounts of aflatoxin in peanut in Mali, Africa. These variables could be considered as potential variables to monitor and predict aflatoxin contamination. Similar studies should be conducted across Africa and an aflatoxin early warning system could be developed by an international agency. Predicting aflatoxin will help identify risk zones where aflatoxin-contaminated peanuts could be kept from distributing among the general public. Alternatively, governmental, nongovernmental, or international agencies could provide supplies of quality peanuts to meet the requirement in these risk zones

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