The Effect of Sorting Farmers' Stock Peanuts by Size and Color on Partitioning Aflatoxin into Various Shelled Peanut Grade Sizes[1]

Thomas B. Whitaker[2]*, Joe W. Dorner[3], Marshall Lamb[4], and Andrew B. Slate (Retired)[5]

ABSTRACT

Farmers' stock peanuts are processed into shelled peanuts using several basic sorting processes. After removal of foreign material and the shelling process, loose shelled kernels and shelled kernels are typically sorted by size into jumbo (J), medium, (M), number one (N1), other edibles (OE), sound splits (SS), and oil stock (OS) grades. Using electronic color sorters, shelled peanuts in each grade size are color sorted where discolored kernels are sorted into a reject category and the better quality peanut kernels are sorted into an accept category. Because aflatoxin contamination is associated with both small kernels and with damaged (discolored) kernels, sorting farmers' stock peanuts by size and by color in the formation of shelled peanuts partitions the aflatoxin in different ways among the various size and color categories. Forty-six 45.4 kg (100 lb) mini-lots, each taken from farmers' stock lots suspected of aflatoxin contamination, were shelled, sized into six grade categories, and each grade (except OS grade) was color sorted into an acceptable and unacceptable category (11 categories per mini-lot). The aflatoxin concentration among the 46 mini-lots varied from less than 1 ppb to 783 ppb omit averaged 73.7 ppb. The aflatoxin in the J, M, N1, OE, SS, and OS grade sizes averaged 42.5, 66.2, 93.6, 116.7, 105.1, and 133.6 ppb, respectively. Only the two largest peanut grades (J and M) contained less aflatoxin on the average than the farmers' stock peanuts before sorting by size. After color sorting, the acceptable portion of the J, M, N1, and OE grades had an aflatoxin reduction on the average of 37.8, 30.9, 28.8, and 32.2%, respectively. Regression equations were developed to predict the aflatoxin in the each grade size (before and after color sorting) as a function of the aflatoxin in the mini-lot.

Key Words: Aflatoxin, color sort, size sort, aflatoxin reduction.

Aflatoxins are hepatotoxic, carcinogenic metabolites produced primarily by the fungi, *Aspergillus flavus* Link and *A. parasiticus* Speare (Wilson and Payne, 1994). Four individual toxins occur naturally, and they are designated B_1, B_2, G_1, and G_2. They are often referred to collectively as aflatoxin. Because aflatoxin contaminates many different food matrices, about 100 countries have established regulatory limits for aflatoxin (Food and Agriculture Organization, 2004). In the USA, the Food and Drug Administration (FDA) has a regulatory limit for total aflatoxins of 20 ng/g or parts per billion (ppb) for all food products. The peanut industry, working with the U.S. Department of Agriculture (USDA), has established a rigorous aflatoxin control program to test shelled peanuts for aflatoxin prior to processing into consumer-ready products. The USDA has established an aflatoxin limit of 15 ng/g for domestic lots of raw shelled peanuts. All domestic lots of raw shelled peanuts are tested for aflatoxin at the shelling plant before shipment to a food manufacturer. The USDA estimates the aflatoxin concentration in each shelled lot produced by a sheller by taking three 22 kg (48 lbs) samples from each lot. The three 22 kg samples must average 15 ng/g aflatoxin or less before the lot can be shipped to the food manufacturer (Adams and Whitaker, 2004). If the three 22 kg samples average more than 15 ng/g aflatoxin, the sheller has the option to crush the lot for oil, remill the lot (process through the shelling plant again), and or blanch (remove the reddish skin from the seed and remove damaged seed with electronic color sorters) the lot. The last two options are routinely used by shellers to remove contaminated kernels from the lot to reduce the lot aflatoxin concentration to a level below the USDA limit of 15 ng/g. Lots that are remilled or blanched must be tested again for aflatoxin before shipment to a food manufacturer.

The USDA aflatoxin control program also includes visual inspection of farmers' stock peanuts at the buying point for the presence of *A. flavus* (called the VAF method). If *A. flavus* is found on a single peanut kernel in the grade sample taken

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[2]U.S. Department of Agriculture, Agricultural Research Service, Box 7625, NC State University, Raleigh, NC, 27695-7625.

[3]U.S. Department of Agriculture, Agricultural Research Service, National Peanut Research Laboratory Box 509, Dawson, GA, 31742.

[4]U.S. Department of Agriculture, Agricultural Research Service, National Peanut Research Laboratory Box 509, Dawson, GA, 31742.

[5]U.S. Department of Agriculture, Agricultural Research Service, Box 7625, NC State University, Raleigh, NC, 27695-7625.

*Corresponding Author: (email: Tom_Whitaker@ncsu.edu)

from a farmer's load during the grading process, the load is classified Segregation 3 and is isolated from loads in which visible *A. flavus* is not found (Segregation 1). Studies have shown that Segregation 3 loads have on average more aflatoxin than Segregation 1 loads (Dickens and Satterwhite, 1971). The peanut industry and the USDA have studied the possibility of replacing the farmers' stock VAF inspection program with a chemical testing program similar to that used with shelled peanuts where samples taken from farmers' stock peanuts would be tested for aflatoxin. Studies have been conducted to measure the uncertainty associated with sampling farmers' stock peanuts for aflatoxin (Whitaker, T.B., *et al.*, 1994a; Whitaker, T.B., *et al.*, 1994b). The information from these studies has been used to develop a method to evaluate the performance of aflatoxin sampling plan designs so that USDA and the peanut industry can develop an effective aflatoxin sampling plan for farmers' stock peanuts (Whitaker, T.B., *et al.*, 1994c; Whitaker, T.B., *et al.*, 1999a; Whitaker, T.B., *et al.*, 1999b).

When designing an aflatoxin-sampling plan for farmers' stock peanuts, the two most important design parameters are the sample size and the accept/reject limit. The accept/reject limit is a threshold value used to classify a farmer's load into categories based upon aflatoxin levels. If, for example, the aflatoxin in a sample taken from a farmer's load is less than or equal to an accept/reject limit, the farmer's load is accepted and classified good; otherwise, the load is rejected and classified bad. Choice of the accept/reject limit can affect both the supply of peanuts and the amount of aflatoxin-contaminated peanuts going into the shelling plant. There are good and bad scenarios associated with defining an accept/reject limit. Low accept/reject limits can limit supply by rejecting more lots, but reduce the number of aflatoxin-contaminated lots going into the shelling plant. High accept/reject limits are less likely to limit supply by accepting more lots, but will allow more aflatoxin-contaminated lots into the shelling plant.

One possible way to objectively define an accept/reject limit for an aflatoxin sampling plan for farmers' stock peanuts is to base the accept/reject limit upon the effectiveness of shelling plant processes to remove aflatoxin-contaminated kernels during the formation of shelled lots. An accept/reject limit for a farmers' stock aflatoxin sampling plan should be established so that shelled lots produced from a farmers' stock lot would have a reasonable chance of being accepted by the current USDA aflatoxin sampling plan for shelled peanuts.

Shelling plant processes can reduce aflatoxin contamination in a shelled lot produced from a farmer's load by removing aflatoxin-contaminated kernels during the various sorting processes used to create a shelled peanut lot. Studies have shown that loose- shelled kernels (LSK), damaged or discolored kernels, and small kernels are at higher risk for aflatoxin contamination than are large, mature peanuts in a farmers' stock lot (Whitaker, T.B. *et al.*, 1998.). In the shelling plant, screens are used to remove LSK from farmers' stock peanuts prior to shelling. After shelling, all kernels are sorted into various grade categories based upon size, and they are passed through electronic color sorters to remove discolored or damaged kernels.

The sheller could develop more effective aflatoxin management strategies and the peanut industry could define an accept/reject limit for an aflatoxin sampling plan if data existed to show how aflatoxin in farmers' stock peanuts is partitioned into various shelled peanut grades. The objective of this study was to determine how aflatoxin in farmers' stock peanuts partitions when shelled peanuts are sorted by size and color into various shelled peanut grade categories.

Materials and Methods

Forty-six loads of runner-type farmers' stock peanuts suspected of being contaminated with aflatoxin were identified with the help of shellers in southwest Georgia and southeast Alabama. A 45 kg (100 lb) portion, called a mini-lot, was removed from each of the 46 identified farmers' stock loads. The 46 mini-lots were sent to the National Peanut Research Laboratory (NPRL) in Dawson, Georgia, for shelling and aflatoxin testing. Prior to processing each mini-lot, an official 1800 g grade sample was removed and graded by the Georgia Federal State Inspection Service (FSIS).

Processing of mini-lots. Each mini-lot was processed in the NPRL pilot shelling plant to simulate current commercial shelling plant processes used to produce shelled peanut lots from farmers' stock peanuts. Each farmers' stock mini-lot consisted of three components: intact pods, LSK, and foreign material. Intact pods usually consist of two peanut kernels incased in a fibrous hull. LSK are peanut kernels loose in the bulk load because the hull broke during harvesting and post harvest handling operations. Foreign material is non-peanut material such as sand, sticks, stones, etc. that are inadvertently collected during digging and harvesting processes.

Each mini-lot was passed through a farmers' stock cleaner designed to separate the foreign material from pods and LSK. The remaining pods and LSK were separated by density using a gravity table. Final separations were done by hand picking. All pods were shelled in a one-quarter-scale sheller identical to shellers used in commercial shelling plants. The sheller was equipped with industry standard screens with various size holes to sort the shelled kernels into six runner grades based upon kernel size.

Shelled kernel grade sizes. Peanut kernels shelled from intact pods (shelled kernels) were separated into jumbo (J), medium (M), number 1 (N1), other edibles (OE), oil stock (OS) and sound splits (SS) grade categories for runner peanuts. A jumbo peanut is defined as a kernel that rides a screen with 21/64 inch wide by ¾ inch long slotted holes (21S). A medium peanut will pass through a 21 S screen, but ride a screen with 18/64 inch wide by ¾ inch long slotted holes (18S). A number 1 peanut (prior to 2003) will pass through an 18 S screen, but ride a screen with 16/64 inch wide by ¾ inch long slotted holes (16S). Other edibles pass through 16S screen, but ride a screen with 17/64 inch diameter round holes (17R). Oil stock peanuts are kernels that pass through a 17R screen. Sound splits are kernels that split during shelling and ride a 17R screen. In 2003, USDA defined a new number 1 (NN1) runner grade to be a peanut kernel that rides a 17R screen. The NN1 grade can be constructed by combining the N1 grade kernels with the other edibles (N1+OE) to represent a seventh grade. The NN1 Grade was not evaluated in this study.

LSK grade sizes. The LSK were separated into the same six grade categories as the shelled kernels, but kept separate.

Electronic color sorting. Peanut kernels in each LSK and shelled kernel grade category, except oil stock, were passed through a Satake ScanMaster electronic color sorter (ECS) (ESM International, Houston, TX). A sheller representative, knowledgeable of ECS equipment, calibrated the ECS to approximate industry rejection rates. For each kernel type (LSK and shelled kernels), the kernels in five grades (J, M, N1, OE, and SS) were each passed through the ECS and separated into accept and reject categories. Oil stock (OS) is not an edible grade and, therefore, was not color sorted.

All kernels from each mini-lot were classified into two kernel types: shelled kernels or loose-shelled kernels. Each kernel type was sized into six grade categories (jumbo, medium, number 1, other edibles, oil stock, and sound splits). Each grade category, except oil stock, was color sorted and classified into accept or reject categories. As a result, all kernels from each 45 kg mini-lot were separated into 22 separate kernel categories.

The mass (weight) and aflatoxin concentration associated with kernels in each of the 22 categories were determined for each of the 46 mini-lots. The hull mass was recorded, but not analyzed for aflatoxin. The hulls were discarded under the assumption that no aflatoxin was associated with the hulls.

Aflatoxin analyses. For kernel categories containing $\leq$300 g of kernels, all kernels were homogenized in a blender for 2 min and extracted with methanol-water (80 + 20, v/v; 2 mL/g). If the kernel mass of a category was >300 g, the entire mass was first ground for 7 min in a vertical cutter mixer to produce a homogeneous paste, then 200 g of the paste was extracted with methanol-water. Aflatoxins were quantified by the high performance liquid chromatographic (HPLC) method (Dorner and Cole, 1988). The HPLC system consisted of a Waters 3.9 × 150 mm Nova-PAK C_{18} column (Waters Inc, Milford, MA) with a mobile phase of water-methanol-butanol (700 + 355 + 12; v/v/v). Instead of using postcolumn iodination to enhance fluorescence of aflatoxins B_1 and G_1, postcolumn derivatization was achieved with a photochemical reactor (Joshua, 1993) placed between the column and a Shimadzu Model RF551 fluorescence detector (Shimadzu, Kyoto, Japan) with excitation and emission wavelengths of 365 and 440 nm, respectively. Injection solvent consisted of methanol-water (62 + 38, v/v) with 0.1% acetic acid. Aflatoxin standards were prepared from crystals according to AOAC method 970.44 (Official Methods of Analysis, 1995), and aflatoxin determinations were not corrected for recovery. Individual aflatoxins were measured and the values reported are for total aflatoxins (ng) per g of peanuts (ng/g; ppb). The kernel mass, aflatoxin concentration, kernels category, and lot identification code were recorded in a spreadsheet for statistical analysis. Using a mass balance, the aflatoxin concentration for the total kernels in each mini-lot was computed by summing the ng of aflatoxin for all kernel categories and dividing by the total kernel weight of all categories.

Results

The kernel mass and aflatoxin concentration associated with the shelled kernels, LSK, and total kernels (shelled kernels + LSK) for each mini-lot is shown in Table 1. The mini-lots are ranked in Table 1 by the aflatoxin concentration among all

Table 1. Kernel mass (kg) and aflatoxin concentration (ng/g) in 46 farmers' stock mini-lots.

	Shelled Kernels		LSK		Total	
Lot Number	Mass (kg)	Aflatoxin (ppb)	Mass (kg)	Aflatoxin (ppb)	Mass (kg)	Aflatoxin (ppb)
143	32.55	0.2	0.26	5.5	32.81	0.3
144	33.46	0.3	0.34	1.9	33.80	0.3
140	34.43	0.4	0.26	15.2	34.69	0.5
138	31.24	0.3	0.32	107.8	31.57	1.4
142	34.00	2.0	0.67	10.5	34.67	2.2
145	33.72	3.0	0.29	0.0	34.01	3.0
137	32.76	3.0	0.30	252.9	33.06	5.3
139	31.70	8.5	0.24	20.0	31.93	8.6
141	32.26	12.2	0.28	0.3	32.53	12.1
136	33.92	13.5	0.24	4.2	34.17	13.5
116	34.57	15.1	1.62	30.5	36.19	15.8
110	32.95	16.1	2.21	21.4	35.17	16.5
111	30.08	16.8	2.37	28.6	32.45	17.7
118	33.18	19.0	2.52	42.3	35.70	20.6
117	32.94	18.1	2.40	88.4	35.34	22.9
120	33.82	24.7	2.67	36.0	36.49	25.6
112	31.00	26.7	1.52	1.4	32.52	25.6
113	34.15	26.7	1.69	6.5	35.83	25.8
115	32.95	27.1	1.54	7.2	34.49	26.2
125	34.16	27.3	5.25	36.7	39.41	28.6
129	33.92	30.1	3.31	14.1	37.23	28.7
128	34.55	29.1	4.13	36.4	38.68	29.9
124	34.69	29.2	4.94	42.8	39.62	30.9
127	35.13	31.6	4.43	26.5	39.56	31.1
126	33.33	36.9	5.48	8.6	38.81	32.9
121	33.87	33.8	4.30	28.5	38.17	33.2
105	26.81	36.4	1.08	24.3	27.89	36.0
122	33.52	31.3	4.20	91.0	37.72	38.0
114	34.34	40.1	1.84	14.8	36.18	38.8
131	37.54	42.1	2.45	38.1	39.99	41.8
130	37.14	43.1	3.25	44.9	40.39	43.3
123	32.52	36.1	3.82	106.4	36.34	43.5
106	30.72	46.7	1.16	15.1	31.88	45.5
109	33.62	48.9	1.45	7.5	35.07	47.2
104	29.62	50.8	1.11	49.2	30.73	50.7
101	30.19	49.9	0.79	101.2	30.98	51.2
107	31.83	51.0	1.40	82.4	33.24	52.4
100	31.12	53.4	0.89	263.8	32.01	59.3
103	31.08	63.3	1.19	71.4	32.26	63.6
119	29.16	64.8	1.33	64.1	30.49	64.8
108	32.87	89.1	1.08	123.7	33.96	90.2
102	28.13	118.4	1.06	2.6	29.19	114.2
134	27.52	275.0	1.68	45.6	29.21	261.8
135	24.96	396.0	1.54	25.2	26.50	374.4
132	36.38	776.6	1.65	179.6	38.03	750.6
133	30.21	806.9	1.10	136.6	31.32	783.3

LSK = loose shelled kernels.

kernels in the mini-lot. The aflatoxin concentration among the 46 mini-lots varied from less than 1 ppb to a high of 783 ppb.

Kernel Mass.

Averaged across the 46 mini-lots, the mass of shelled kernels and LSK was 32.5 kg (71.6 lb) and 1.9 kg (4.2 lb), respectively (Table 1). The average mass of all kernels (shelled kernels + LSK) was 34.4 kg (75.8 lb). On the average, all kernels (both shelled and LSK) and hulls accounted for 75 and 25%, respectively, of the total mass of the mini-lots. On the average, shelled kernels and LSK accounted

Table 2. Summary of kernel mass (g) for each grade and color sort category summed across all 46 mini-lots.

Shell Type	Sort	Grade Size						All Sizes
		J	M	N1	OE	SS	OS	
Shelled Kernels	Accept (g)	271942.3	637852.3	94834.2	41613.3	157435.5		1203677.5
	Reject (g)	41567.9	112002.9	32423.3	13290.5	57167.2	34478.1	290930.0
	Total (g)	313510.2	749855.2	127257.5	54903.7	214602.7	34478.1	1494607.5
LSK	Accept (g)	5960.3	16184.4	5112.1	3692.3	27451.9		58401.0
	Reject (g)	1701.0	5774.3	2254.4	1605.7	7974.3	9961.1	29270.8
	Total (g)	7661.3	21958.8	7366.5	5298.0	35426.2	9961.1	87671.8
Shelled Kernels & LSK	Accept (g)	277902.6	654036.8	99946.2	45305.6	184887.4		1262078.5
	Reject (g)	43268.9	117777.2	34677.7	14896.2	65141.5	44439.2	320200.8
	Total (g)	321171.5	771814.0	134623.9	60201.8	250028.9	44439.2	1582279.3

LSK = Loose shelled kernels. J = jumbo grade. M = medium grade. N1 = number one grade. OE = other edibles grade. SS = sound splits grade. OS = oil stock grade.

for 94.5% and 5.5%, respectively, of the total kernel mass. The percentage of shelled kernels (LSK) varied from a low of 85.9% (14.1%) to a high of 99.3% (0.7%).

Shelled kernels. Table 2 shows the total mass of shelled kernels summed over all 46 mini-lots for each of the six grades. Dividing the total mass by 46 (number of mini-lots), the average mass of shelled kernels in the J, M, N1, OE, SS, and OS grades is 6.8 kg (21%), 16.3 kg (50.2%), 2.8 kg (8.5%), 1.2 kg (3.7%), 4.7 kg (14.4%), and 0.7 kg (2.3%) of all shelled kernel (32.5 kg), respectively. The larger kernels in the J and M grades accounted for about 71.2% of all shelled kernel mass. The percentage of the shelled kernels sorted into each grade size was fairly stable across all 46 mini-lots. For example, the range of shelled kernels in the M grade varied from 48.3% to 55.3%.

Each shelled kernel grade, except OS, was color sorted and separated into accept and reject categories. Table 2 shows the total mass of shelled kernels, summed across all 46 mini-lots, in the accept and reject categories for each of the six grade sizes. All shelled kernels in the OS grade were classified as rejects. On the average, 13.3%, 14.9%, 25.5%, 24.2%, and 26.6% of the shelled kernels in the J, M, N1, OE, and SS grades, respectively, were classified by color sorting as rejects. The fewest shelled kernels were removed from the J and M grades, which are usually considered the highest quality peanuts. About the same percentage of shelled kernels were removed from the N1, OE, and SS grades. Averaged over all grades and all mini-lots, color sorting classified about 19.5% of the shelled kernels as rejects.

LSK. The LSK were sized in a similar manner as the shelled kernels. Table 2 shows the total mass of LSK summed over all 46 mini-lots for each of the six grades. Dividing the total mass by 46 (number of mini-lots), the average mass of LSK in the J, M, N1, OE, SS, and OS grades was 0.17 kg (8.7%), 0.47 kg (25.0%), 0.16 kg (8.4%), 0.11 kg (6.0%), 0.77 kg (40.4%), and 0.22 kg (11.4%), respectively. It is not surprising that over 40% of the LSK were in the split (SS grade) category compared to 3.7% splits in the shelled kernels. The LSK are probably more prone to splitting because LSK are not protected by the hull. The larger peanuts in the J and M grades accounted for less than 33.7% of the LSK kernels compared to 71.2% for the shelled kernels.

The LSK were color sorted in a manner similar to the shelled kernels. Table 2 shows the total mass of LSK, summed across all 46 mini-lots, in the accept and reject categories for each of the six grade sizes. Each LSK grade, except OS, was color sorted into accept and reject categories. As with shelled kernels, all LSK in the OS grade were classified as rejects. On the average, 22.2%, 26.3%, 30.6%, 30.3%, and 22.5% of the LSK in the J, M, N1, OE, and SS grades, respectively, were classified as rejects by color sorting. Generally a higher percentage of LSK were removed from each grade than was the case with shelled kernels. Averaged over all grades and all mini-lots, color sorting classified about 33.4% of the LSK as rejects compared to 19.5% of the shelled kernels.

All kernels. The shelled kernels and the LSK were combined mathematically to investigate how all kernels (shelled kernels + LSK) were partitioned into the different grade sizes and into the accept/reject categories by color sorting. One would expect the results to be very similar to shelled kernel results since the LSK account for only 5.5% of the total kernel mass in the mini-lot. Table 2 shows the total mass of all kernels (shelled kernels + LSK)

Table 3. Mean aflatoxin concentrations (ng/g) in each grade and color sort category of 46 peanut mini-lots. (NOTE: delete all ppb occurrences).

Shell Type	Sort	Grade Size						All Sizes
		J	M	N1	OE	SS	OS	
Shelled Kernels	Accept (ppb)	26.4	46.4	68.2	81.1	119.9		54.4
	Reject (ppb)	147.6	185.0	168.8	207.5	117.0	151.8	161.6
	Total (ppb)	42.4	67.1	93.9	111.7	119.1	151.8	75.3
LSK	Accept (ppb)	29.2	20.2	37.6	57.7	19.7		24.8
	Reject (ppb)	96.0	79.0	207.1	425.5	20.7	70.8	90.2
	Total (ppb)	44.0	35.7	89.5	169.2	19.9	70.8	46.6
Shelled Kernels & LSK	Accept (ppb)	26.4	45.7	66.7	79.2	105.0		53.0
	Reject (ppb)	145.6	179.8	171.3	231.0	105.2	133.6	155.1
	Total (ppb)	42.5	66.2	93.6	116.7	105.1	133.6	73.7

LSK = Loose shelled kernels. J = jumbo grade. M = medium grade. N1 = number one grade. OE = other edibles grade. SS = sound splits grade. OS = oil stock grade.

summed over all 46 mini-lots for each of the six grades. Dividing the total kernel mass by 46 (number of mini-lots), the average mass of all kernels in the J, M, N1, OE, SS, and OS grades was 0.70 kg (20.3%), 16.8 kg (48.8%), 2.9 kg (8.5%), 1.3 kg (3.8%), 5.4 kg (15.8%), and 1.0 kg (2.8%), respectively. The larger kernels in the J and M grades accounted for about 69.1% of all kernel mass. These results are very similar to that described above for shelled kernels.

Each grade containing all kernels, except OS, were color sorted and separated into accept and reject categories. All kernels in the OS grade were classified as rejects. On the average, 13.5%, 15.3%, 25.8%, 24.7%, and 26.1% of all kernels in the J, M, N1, OE, and SS grades, respectively, were classified into the reject category by color sorting. As with the shelled kernels, the fewest kernels were removed from the J and M grades. About the same percentage of kernels in the N1, OE, and SS grades were color sorted into the reject category. Averaged over all grades and all mini-lots, the ECS classified about 20.2% of all kernels as rejects.

Aflatoxin contamination.

The aflatoxin concentrations among the 46 mini-lots (all kernels) varied from less than 1 ppb to 783 ppb (Table 1). The average aflatoxin concentration among all kernels, shelled kernels, and LSK was 73.7, 75.3, and 46.6 ppb, respectively (Table 3). Finding more aflatoxin in the shelled kernels than LSK was somewhat unexpected since LSK have been shown to be one of the high-risk categories for aflatoxin in farmers' stock peanuts (**9**). How aflatoxins partitioned into the various grade sizes and into accept and reject categories by color sorting is shown below for shelled kernels, LSK, and all kernels (shelled kernels + LSK) using Table 3.

Shelled kernels. The average aflatoxin in all shelled kernels was 75.3 ppb. After sorting into the 6 grade sizes, the average aflatoxin concentration in J, M, N1, OE, SS, and OS was 42.4, 67.1, 93.9, 111.7, 119.1, and 151.8 ppb, respectively (Table 3). The aflatoxin concentration was less in the large J and M grades and higher in the remaining four grades than the overall average of 75.3 ppb. Sorting the shelled kernels by size does appear to reduce the aflatoxin concentration among the larger kernel grade sizes (J and M) and concentrate the aflatoxin in the poor quality grades such as the OE and OS.

Each shelled kernel grade, except OS, was color sorted and classified into accept and reject categories. Color sorting did a good job in partitioning the contaminated shelled kernels into the reject category in all but the SS grade. For the J grade, the aflatoxin concentration in all shelled kernels before color sorting, shelled kernels color sorted into the accept category, and shelled kernels sorted into the reject category was 42.4, 26.4, and 147.6 ppb, respectively (Table 3). The aflatoxin concentration in all shelled J grade kernels was reduced from 42.4 ppb to 26.4 ppb in the accept category (37.9% reduction). Similar reductions of 30.9%, 27.3%, and 27.4% were obtained for the M, N1, and OE grades, respectively. For the SS grade, the aflatoxin concentration remained essentially unchanged after color sorting. There is no obvious explanation why color sorting was not effective in partitioning aflatoxin-contaminated split kernels into the reject category for the SS grade.

LSK. The average aflatoxin in all LSK was 46.6 ppb. After sorting into the six grade sizes, the average aflatoxin concentration in J, M, N1, OE,

SS, and OS was 44.0, 35.7, 89.5, 169.2, 19.9, and 70.8 ppb, respectively (Table 3). The aflatoxin concentration was less in the J, M, and SS grades and higher in the N1, OE, and OS grades than the overall average of 46.6 ppb. Sorting LSK by size did not dramatically reduce the aflatoxin concentration except in the split (SS) grade (19.9 ppb). However, it did concentrate the aflatoxin in the smaller size grades (OE and OS).

As with the shelled kernels, each LSK grade except the OS grade, was color sorted and classified into accept and reject categories. Color sorting was an effective method of partitioning the contaminated LSK into the reject category for each grade except the SS grade. The aflatoxin concentration in the LSK J grade was reduced from 44.0 ppb to 29.2 ppb in the accept category (33.7% reduction). Similar reductions of 43.4%, 57.9%, and 65.9% in aflatoxin concentration were obtained for the M, N1, and OE grades, respectively. The ability of the ECS to remove aflatoxin from all LSK grades was similar to that achieved with shelled kernels.

All kernels. The average aflatoxin concentration among all kernels (shelled kernels plus LSK) for all 46 mini-lots was 73.7 ppb. This was determined mathematically using a mass balance for each grade size and color sort category for each mini-lot. After sorting into the six grade sizes, the average aflatoxin concentration in J, M, N1, OE, SS, and OS grades was 42.5, 66.2, 93.6, 116.7, 105.1, and 133.6 ppb, respectively (Table 3). The aflatoxin concentration was lowest in the larger J and M grade sizes and highest in the N1, OE, SS, and OS grades. Sorting all kernels by size does appear to reduce the aflatoxin concentration among the larger kernel grade sizes and concentrate the aflatoxin in the poorer quality grades such as the OE and OS grades.

Each kernel grade, except OS grade, was color sorted and separated into accept and reject categories. Color sorting was an effective method of partitioning the contaminated kernels into the reject category in all but the SS grade. For the J grade, the aflatoxin concentration in all unsorted kernels, kernels in the accept category, and kernels in the reject category was 42.5, 26.4, and 145.6 ppb, respectively (Table 3). The aflatoxin concentration in all J grade kernels was reduced from 42.5 ppb to 26.4 ppb in the acceptable category (37.8% reduction). Similar reductions of 30.9%, 28.8%, and 32.2% were obtained for the M, N1, and OE grades, respectively. The aflatoxin concentration in the OS grade was 133.6 ppb. For the SS grade, the aflatoxin concentration among all kernels before color sorting, kernels in the accept category, and kernels in the reject category was 105.1 ppb, 105.0 ppb, and 105.2 ppb, respectively. As was the case with each kernel type (shelled kernels and LSK), there is no obvious explanation why color sorting was not an effective method of partitioning aflatoxin-contaminated kernels into the reject category for the split SS grade.

Effect of mini-lot aflatoxin concentration.

The aflatoxin concentration among the 46 mini-lots varied from less than 1 ppb to 783 ppb (Table 1) and averaged 73.7 ppb among all 46 mini-lots (Table 3). The previous discussion concerning how aflatoxin was partitioned into the six grade sizes and into the two-color sort categories (accept and reject) for each grade or a total of 11 categories were based on the average of all 46 lots. It was also important to know if aflatoxin in the farmers' stock peanuts (mini-lot) was partitioned into the 11 categories in the same way for mini-lots with low levels of aflatoxin as mini-lots with high levels of aflatoxin. How aflatoxin in each mini-lot is partitioned into the six grade sizes and into the accept and reject categories for each grade is shown below for all kernels (shelled kernels plus LSK).

Grade sizes with no color sorting. For each farmers' stock mini-lot, the aflatoxin concentrations for the jumbo (C_J), medium (C_M), number 1 (C_{N1}), other edibles (C_{OE}), sound splits (C_{SS}), and oil stock (C_{OS}) grade sizes are plotted versus the mini-lot concentration, C_L, in a full-log plot in Figures 1, 2, 3, 4, 5, and 6, respectively. The aflatoxin values are plotted in the log scale to give more weight to the small aflatoxin values and less weight to the high aflatoxin values. Because the points in each of the full-log plots appear to be linear, a regression was performed using the power function shown in Equation 1 for the jumbo grade.

$$C_J = aC_L^b, \tag{1}$$

where C_J is the aflatoxin concentration of all kernels in the J grade size, C_L is the aflatoxin concentration in all kernels in the farmers' stock mini-lot, and a and b are constants determined from the regression analysis. From a regression analysis on the log values, the functional relationship between aflatoxin concentration in each grade and the aflatoxin concentration in the mini-lot is shown below for each of the six grades.

$$C_J = 0.0327\, C_L^{1.531} \tag{2}$$

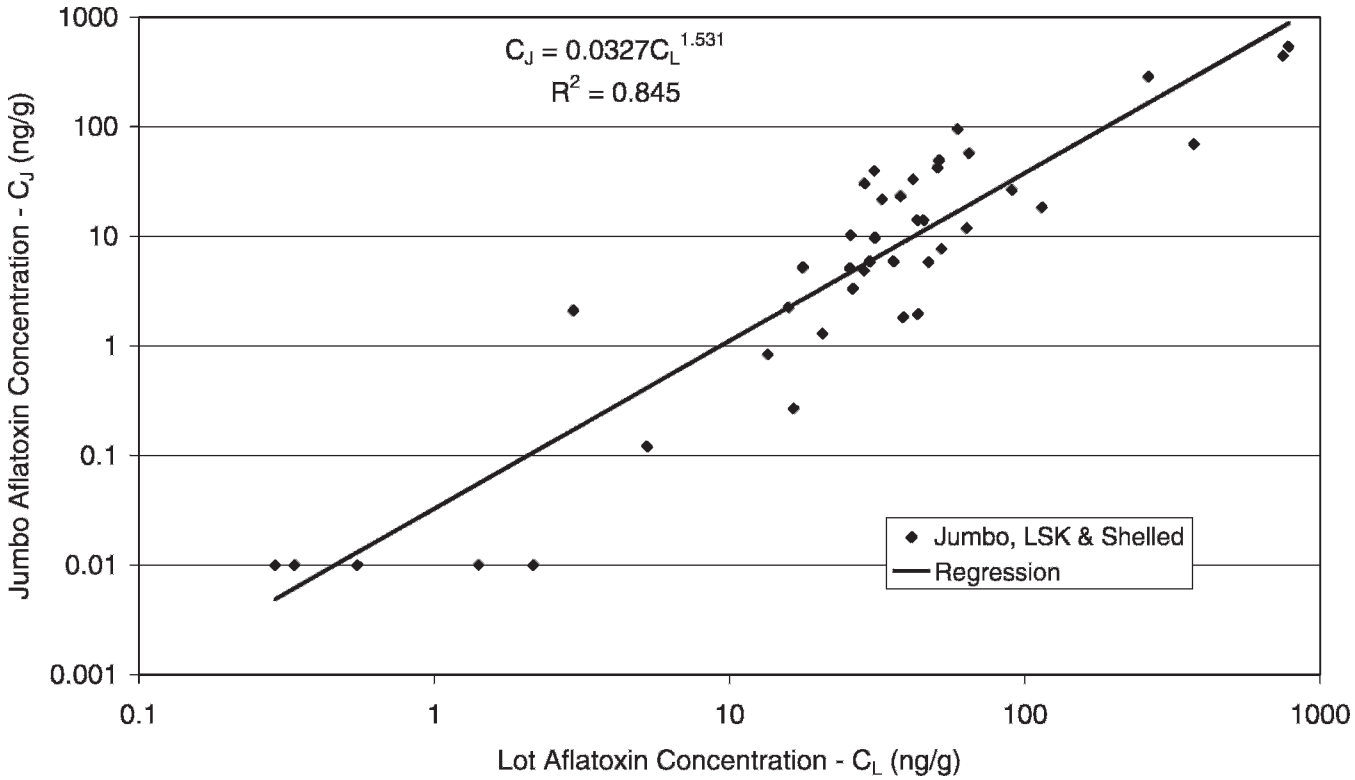

Fig. 1. Aflatoxin concentration among all jumbo grade peanut kernels before color sorting (C_J) versus aflatoxin concentration among all peanut kernels in the farmers' stock mini-lot (C_L).

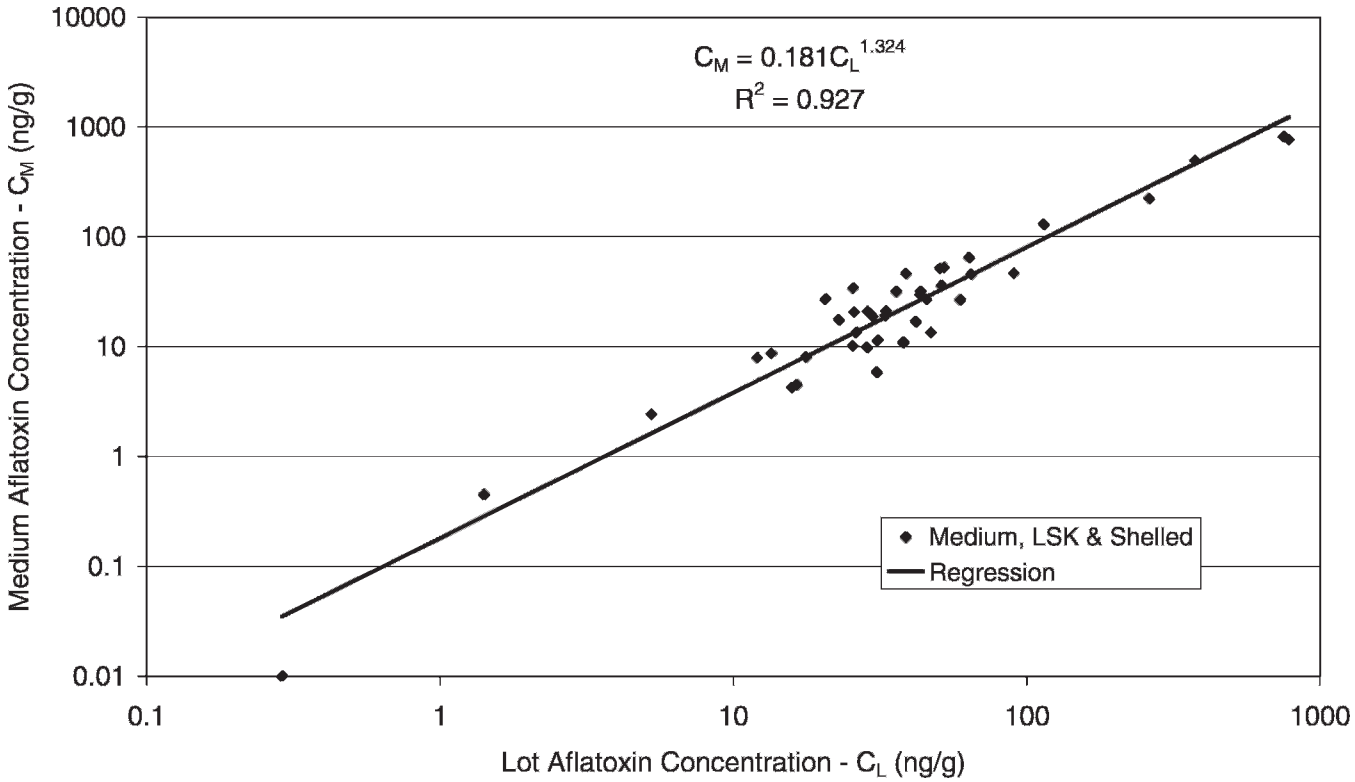

Fig. 2. Aflatoxin concentration among all medium grade peanut kernels before color sorting (C_M) versus aflatoxin concentration among all peanut kernels in the farmers' stock mini-lot (C_L).

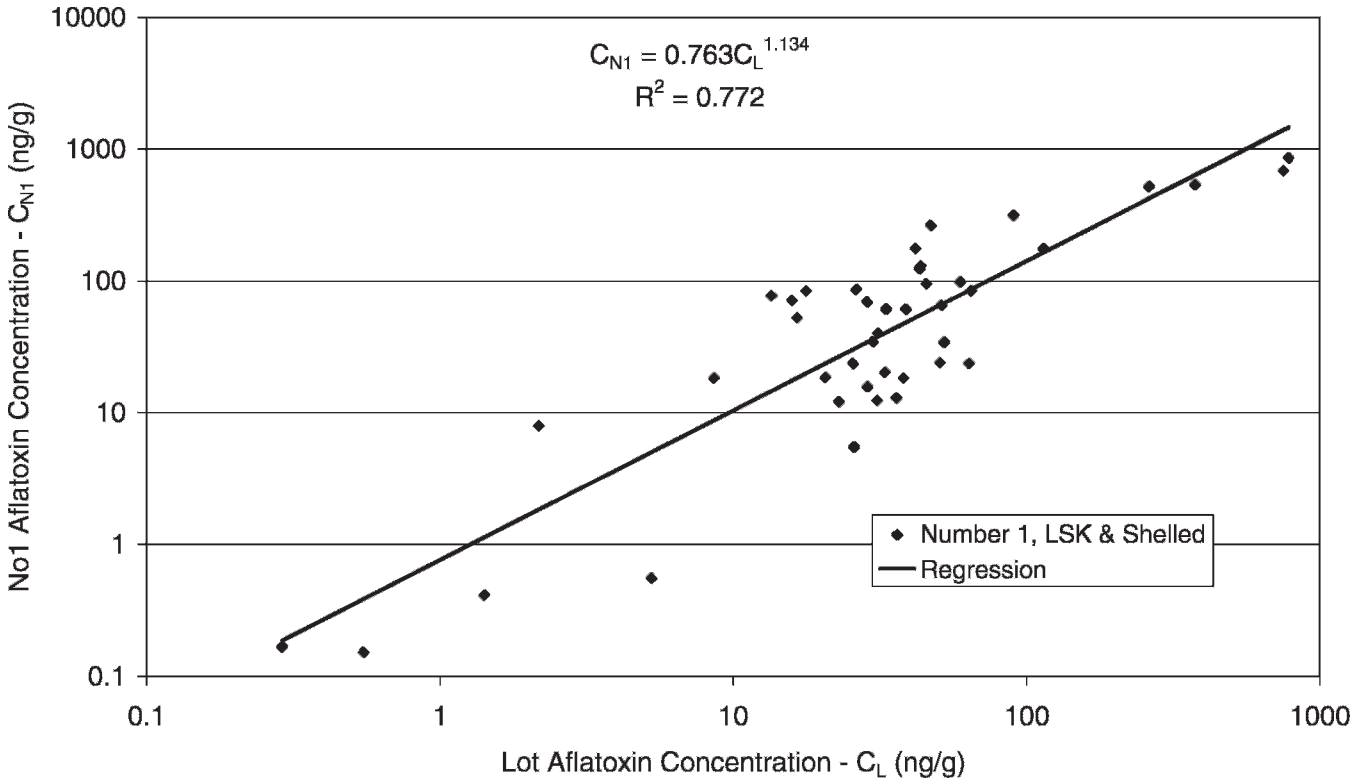

Fig. 3. Aflatoxin concentration among all number 1 grade peanut kernels before color sorting (C_{N1}) versus aflatoxin concentration among all peanut kernels in the farmers' stock mini-lot (C_L).

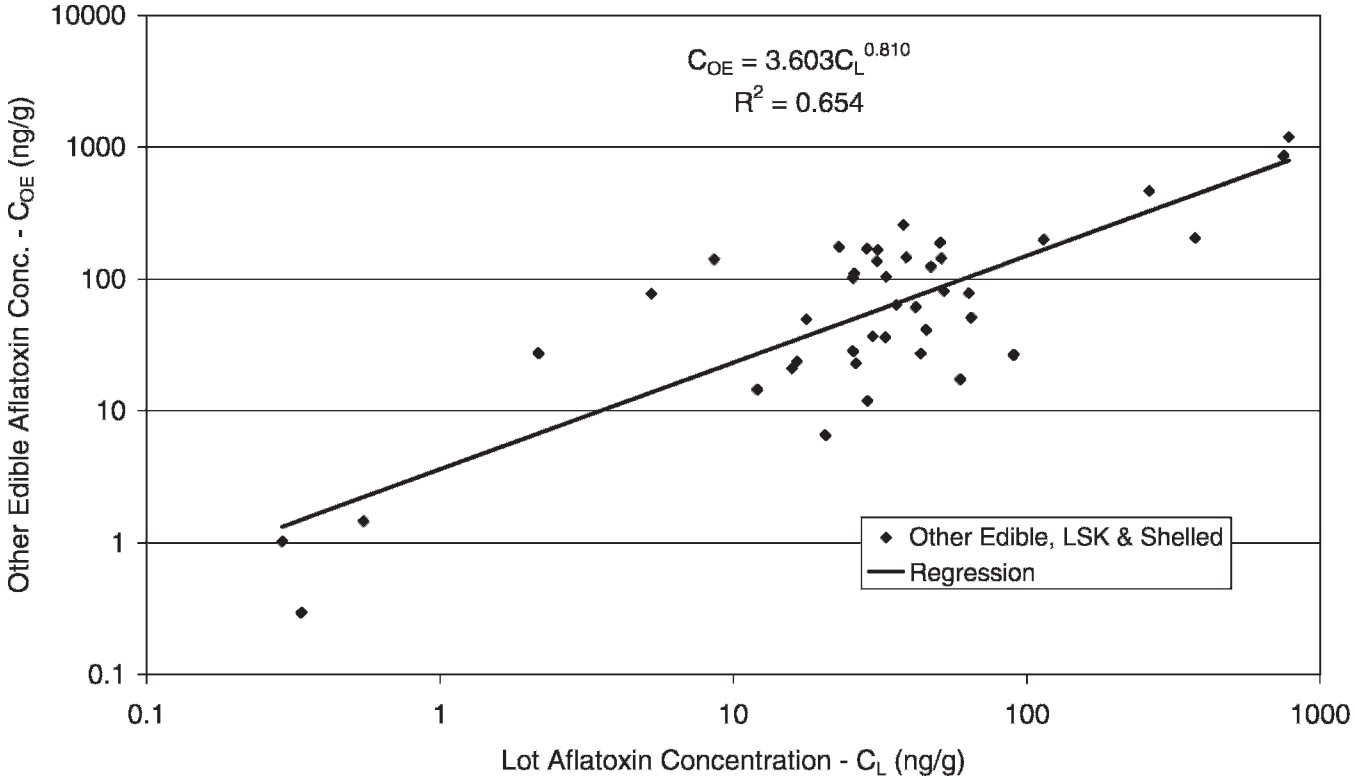

Fig. 4. Aflatoxin concentration among all other edible grade peanut kernels before color sorting (C_{OE}) versus aflatoxin concentration among all peanut kernels in the farmers' stock mini-lot (C_L).

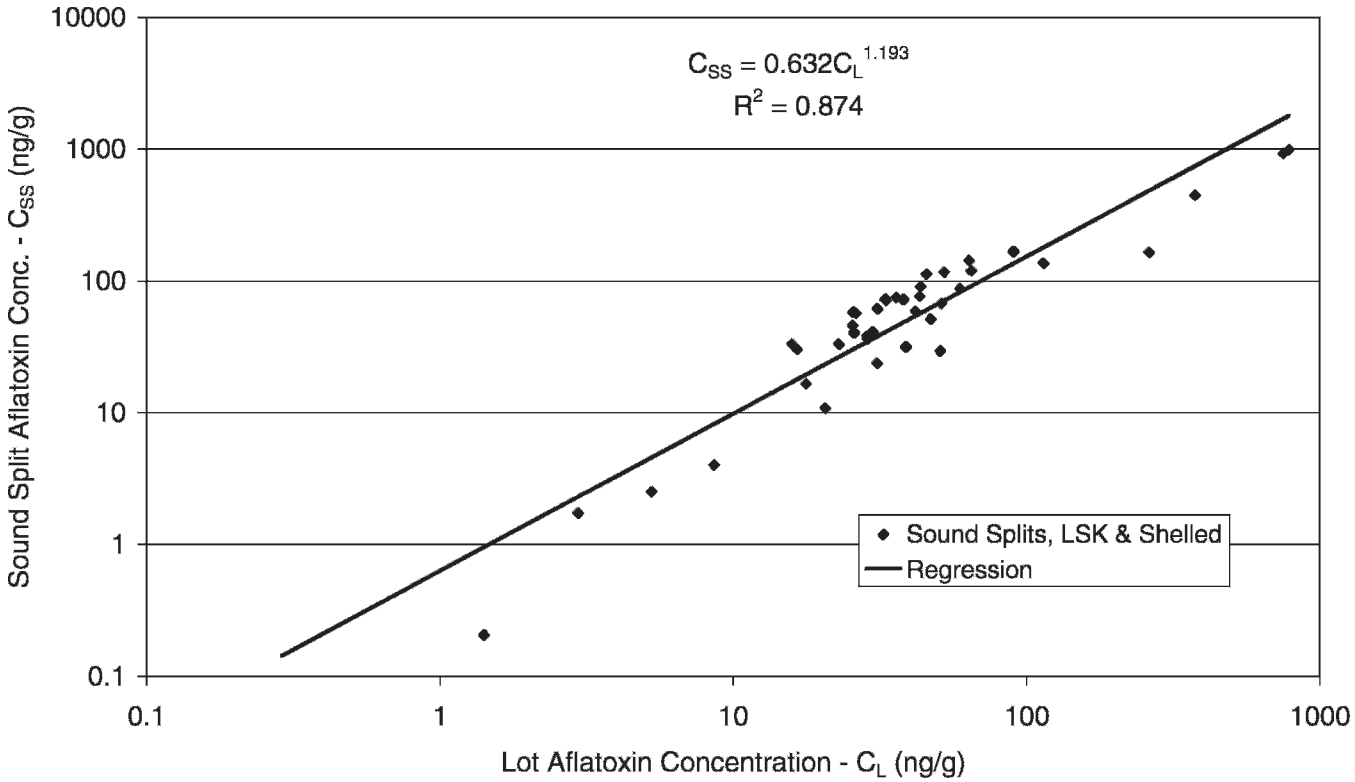

Fig. 5. Aflatoxin concentration among all sound split grade peanut kernels before color sorting (C_{SS}) versus aflatoxin concentration among all peanut kernels in the farmers' stock mini-lot (C_L).

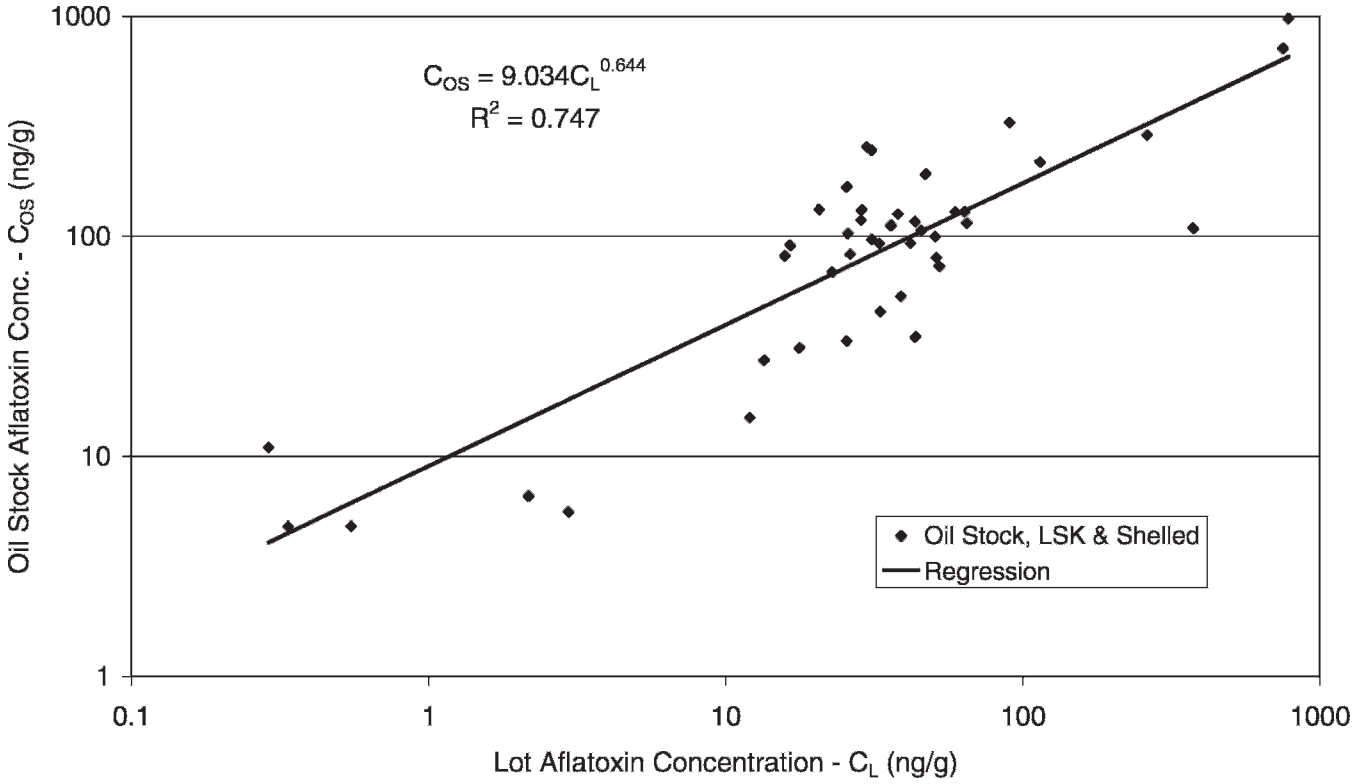

Fig. 6. Aflatoxin concentration among all oil stock grade peanut kernels (C_{OS}) versus aflatoxin concentration among all peanut kernels in the farmers' stock mini-lot (C_L).

$$C_M = 0.181\ C_L^{1.324} \quad (3)$$

$$C_{N1} = 0.763\ C_L^{1.134} \quad (4)$$

$$C_{OE} = 3.603\ C_L^{0.810} \quad (5)$$

$$C_{SS} = 0.632\ C_L^{1.193} \quad (6)$$

$$C_{OS} = 9.034\ C_L^{0.644} \quad (7)$$

The coefficients of determination (R^2) associated with regression equations 2, 3, 4, 5, 6, and 7 are 0.845, 0.927, 0.772, 0.654, 0.874, and 0.747, respectively. Regression equations 2 through 7 are plotted in Figures 1 through 6 along with the measured aflatoxin concentrations in each grade size and mini-lot. Aflatoxin concentrations for some mini-lots are not shown in Figures 1 through 6 because concentrations exceed 95% confidence limit and were considered outliers.

It is interesting that, except for the SS grade, the regression coefficients "a" and "b" increase and decrease, respectively, as the size of the peanut kernels decreases. Although the SS grade is listed between the OE and OS grades, the majority of split kernels were formed from jumbo and medium sized kernels. The way the regression coefficients vary reflects the propensity for aflatoxin to be associated with smaller peanut kernels.

If the value of the exponent (b coefficient) on the C_L term in equations 2 through 7 is greater than 1.0, the percent aflatoxin reduction (gain) among kernels in a grade is less at high mini-lot concentrations than mini-lots with low concentrations. The opposite is true when the "b" coefficient is less than 1.0. If the "b" coefficient is equal to 1.0, the percent aflatoxin reduction would be constant regardless of the mini-lot aflatoxin concentration.

For example, if a farmers' stock lot contains 100.0 ppb (C_L=100), then from equations 2 through 7 the predicted aflatoxin concentration among shelled peanuts in the J, M, N1, OE, SS, and OS grades, before color sorting, would be 37.7, 80.5, 141.4, 150.2, 153.7, and 175.3 ppb, respectively. Therefore, when sizing farmers' stock peanuts at 100.0 ppb into the six grade sizes before color sorting, the percent reduction (gain) in the J, M, N1, OE, SS, and OS is 62.3, 19.5, (41.4), (50.2), (53.7), and (75.3)%, respectively. As noted earlier when using the average among the 46 mini-lots, only the J and M grades had less aflatoxin than the mini-lot concentration.

Electronic color sort categories. After the peanut kernels are sorted by size into the six grades, all kernels in each grade (except the OS grade) were color sorted into accept and reject categories. The damaged or discolored kernels are detected and sorted into a reject category. The remaining kernels are classified into an accept category. The aflatoxin concentrations in the accept category of the J (C_{JA}), M (C_{MA}), N1 (C_{N1A}), OE (C_{OEA}), and SS (C_{SSA}) grades is plotted versus the aflatoxin concentration in all kernels in the J (C_J), M (C_M), N1 (C_{N1}), OE (C_{OE}), and SS (C_{SS}) grades before color sorting in a full-log plot in Figures 7, 8, 9, 10, and 11, respectively. From a linear regression analysis of the log values, the functional relationship between aflatoxin concentration in the accept portion of the grade and the aflatoxin in all kernels in the grade before color sorting is shown in equations 8 through 12 for the J, M, N1, OE, and SS grades respectively.

$$C_{JA} = 0.666\ C_J^{0.863} \quad (8)$$

$$C_{MA} = 0.871\ C_M^{0.947} \quad (9)$$

$$C_{N1A} = 0.569\ C_{N1}^{1.032} \quad (10)$$

$$C_{OEA} = 0.802\ C_{OE}^{0.943} \quad (11)$$

$$C_{SSA} = 1.358\ C_{SS}^{0.930} \quad (12)$$

The coefficients of determination (R^2) associated with regression equations 8 through 12 are 0.907, 0.985, 0.899, 0.903, and 0.986, respectively. Regression equations 8 through 12 are plotted in Figures 7 through 11 along with the measured aflatoxin concentrations for each grade, respectively. Aflatoxin concentrations for some mini-lots are not shown in Figures 7 through 11 because concentrations exceed 95% confidence limit and were considered outliers.

When the value of the "b" coefficient or exponent on the C term in equations 8 through 12 is less than 1.0, the color sorter is more efficient at detecting aflatoxin contaminated kernels at high concentrations than at low concentrations. The "b" coefficient on the C term for the N1 grade is approximately 1.0 indicating that the percentage of aflatoxin partitioned into the reject category by color sorting was approximately the same regardless of the aflatoxin in all kernels in the N1 grade before color sorting.

If each grade contains 100 ppb of aflatoxin before color sorting, then the aflatoxin in

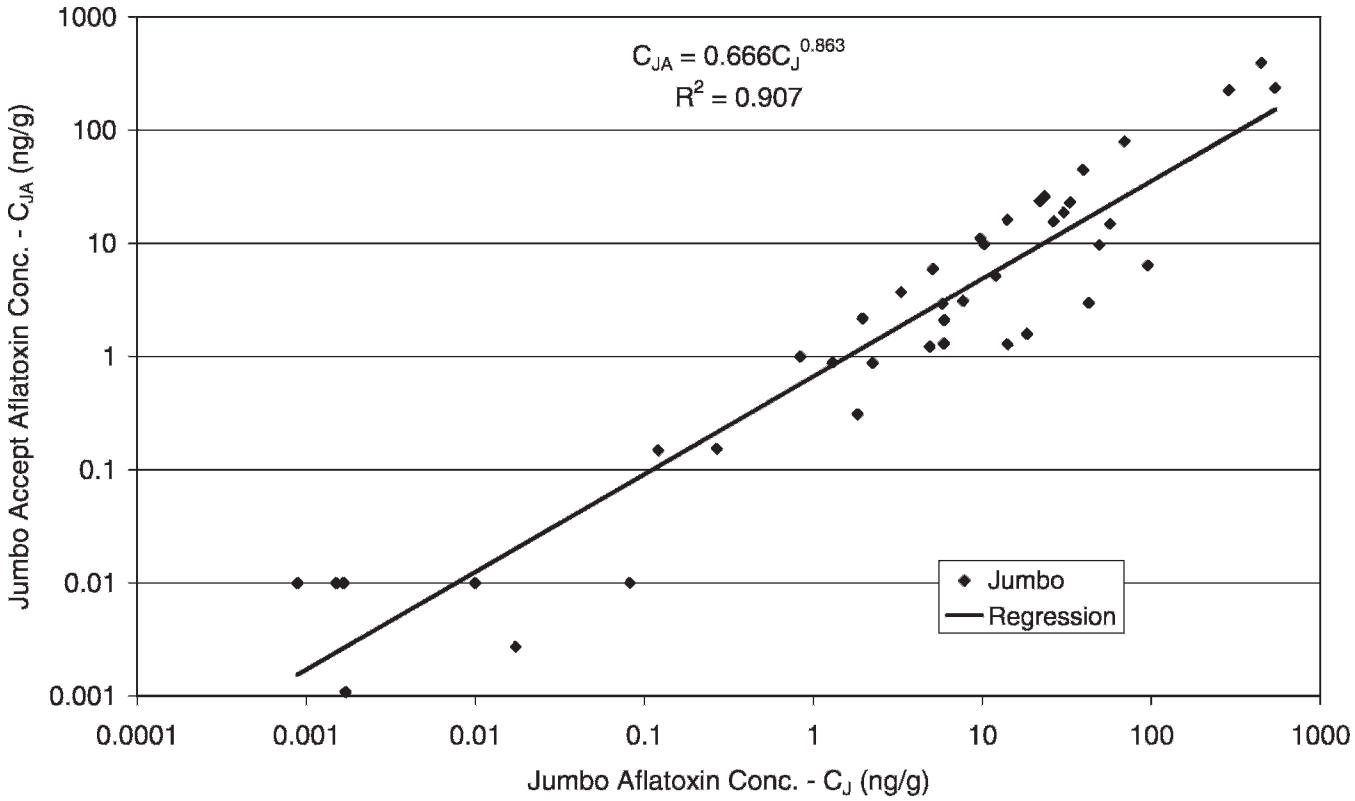

Fig. 7. Aflatoxin concentration among all jumbo grade peanut kernels accepted by color sorting (C_{JA}) versus aflatoxin concentration among all jumbo grade peanut kernels before color sorting (C_J).

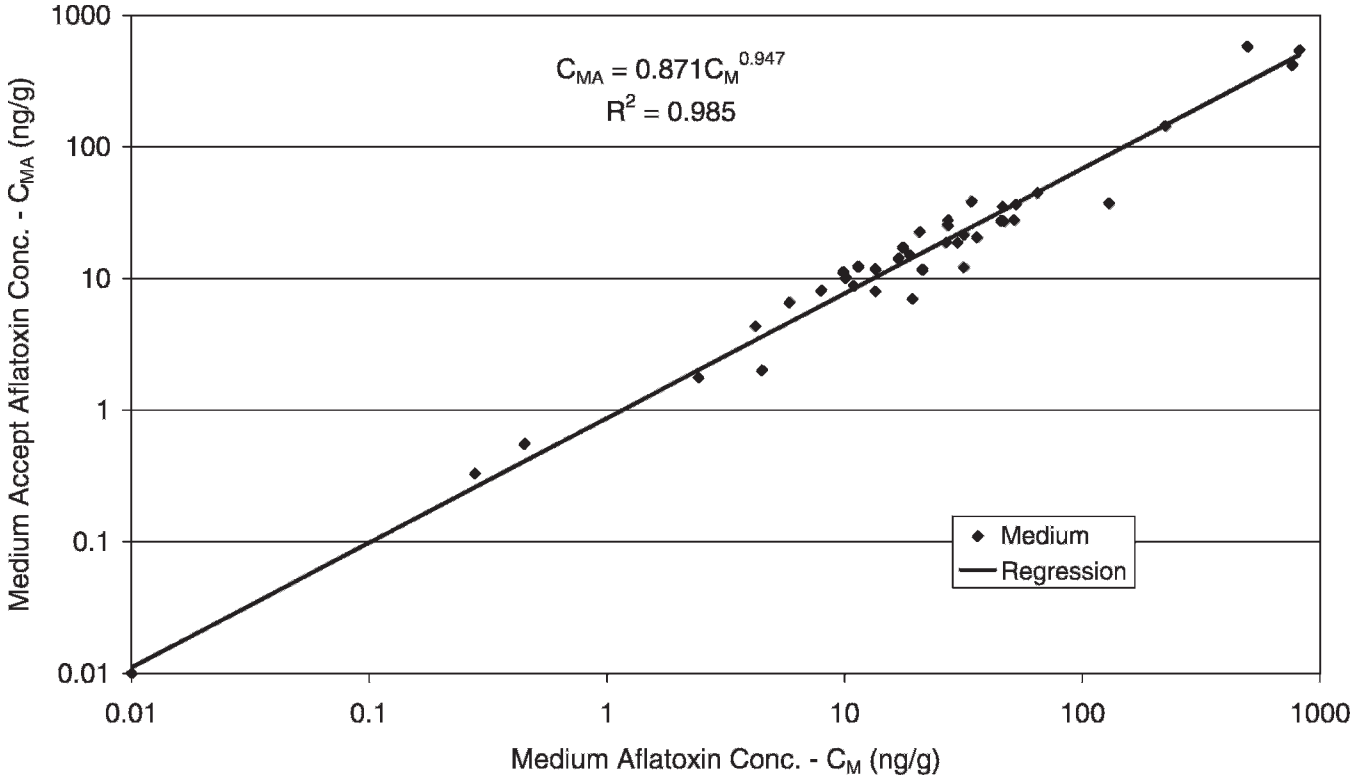

Fig. 8. Aflatoxin concentration among all medium grade peanut kernels accepted by color sorting (C_{MA}) versus aflatoxin concentration among all medium grade peanut kernels before color sorting (C_M).

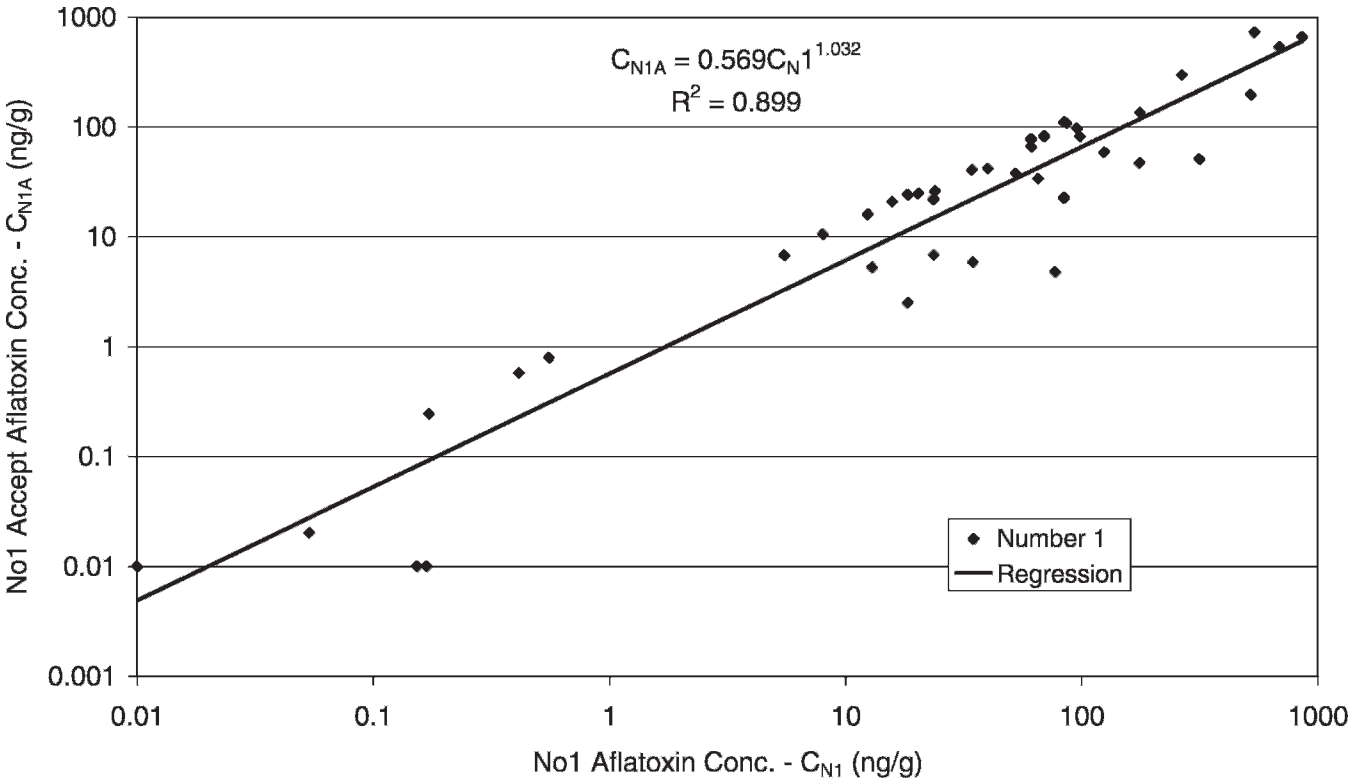

Fig. 9. Aflatoxin concentration among all number 1 grade peanut kernels accepted by color sorting (C_{N1A}) versus aflatoxin concentration among all number 1 grade peanut kernels before color sorting (C_{N1}).

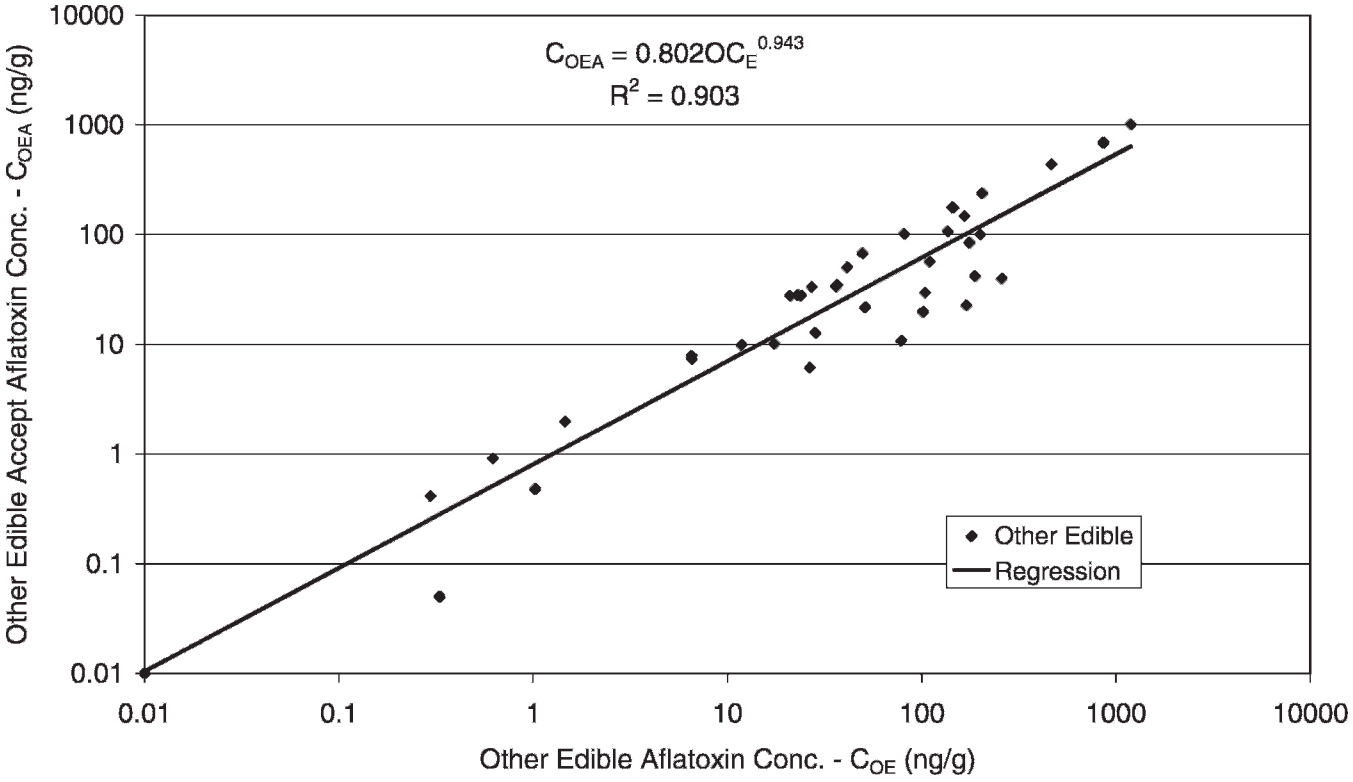

Fig. 10. Aflatoxin concentration among all other edible grade peanut kernels accepted by color sorting (C_{OEA}) versus aflatoxin concentration among all other edible grade peanut kernels before color sorting (C_{OE}).

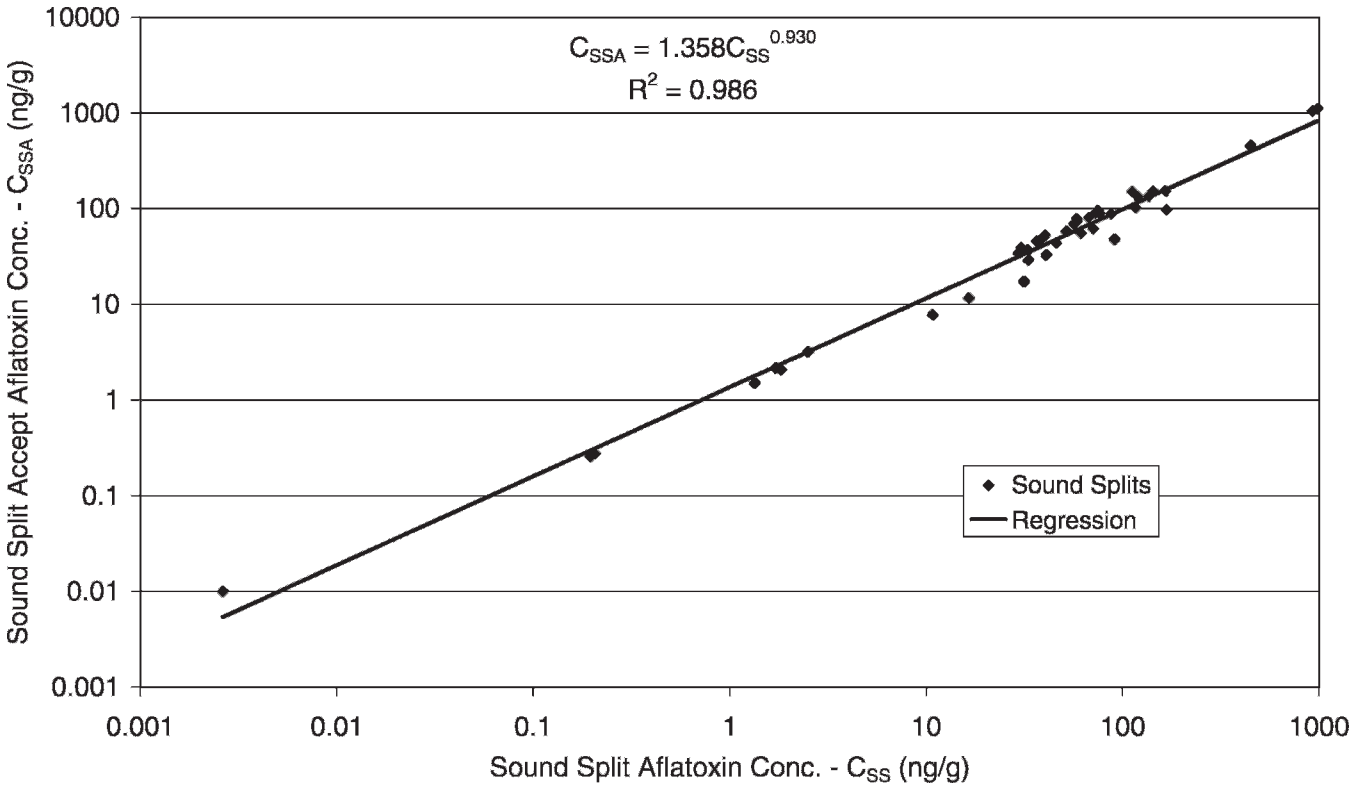

Fig. 11. Aflatoxin concentration among all sound split grade peanut kernels accepted by color sorting (C_{SSA}) versus aflatoxin concentration among all sound split grade peanut kernels before color sorting (C_{SS}).

the accepted portion after color sorting for the J, M, N1, OE, and SS grades can be predicted from equations 8 through 12 to be 35.4, 68.2, 65.9, 61.7, and 98.4 ppb, respectively. With the exception of the SS grade, the color sorters were able to significantly reduce the aflatoxin in the accepted portion of each grade. The percent reductions associated with color sorting the J, M, N1, OE, and SS grades are 64.6, 31.8, 34.1, 38.3, and 1.6%, respectively. Color sorting peanut kernels was an effective method of concentrating aflatoxin-contaminated kernels into the reject category for each grade except the SS grade.

Predicting aflatoxin in shelled peanut grades after color sorting knowing the aflatoxin in farmers' stock peanuts.

Because the aflatoxin concentration in the accepted portion of a grade after color sorting is a function of the aflatoxin in the grade before color sorting and because aflatoxin in the grade before color sorting is a function of the aflatoxin in the mini-lot (C_L), the aflatoxin in the accept category of a specific grade of shelled peanuts can be predicted from the aflatoxin in the farmers' stock lot (C_L). For example, if $C_{JA} = f(C_J)$ and $C_J = f(C_L)$, then aflatoxin in jumbo accept, C_{JA}, can be predicted by knowing the aflatoxin in the farmers' stock lot, C_L. Substituting the relationship for C_J in equation 2 into equation 8, an equation relating C_{JA} to C_L can be derived.

$$C_{JA} = 0.666 \left(0.0327\ C_L^{1.531}\right)^{0.863} \qquad (13)$$

Simplifying,

$$C_{JA} = 0.0348\ C_L^{1.321} \qquad (14)$$

Similar equations can be derived to predict the aflatoxin in the accepted portion of each of the remaining grades of shelled peanuts knowing the aflatoxin in the farmers' stock lot. From equations 3 and 9, the aflatoxin in the M accepts can be predicted from equation 15.

$$C_{MA} = 0.173\ C_L^{1.254} \qquad (15)$$

From equations 4 and 10, the aflatoxin in the N1 accepts can be predicted from equation 16.

$$C_{N1A} = 0.430\ C_L^{1.170} \qquad (16)$$

From equations 5 and 11, the aflatoxin in the OE accepts can be predicted from equation 17.

$$C_{OEA} = 2.686\, C_L^{0.763} \quad (17)$$

From equations 6 and 12, the aflatoxin in the SS accepts can be predicted from equation 18.

$$C_{SSA} = 0.886\, C_L^{1.109} \quad (18)$$

The OS grade was not color sorted and all kernels were classified as a reject category.

Equations 14 through 18 can be used to predict how aflatoxin in a farmer's lot will be partitioned into the six acceptable shelled peanut grades after color sorting. For example if a farmers' stock lot contains 100 ppb of aflatoxin (C_L), then the predicted aflatoxin concentration in the J, M, N1, OE, and SS grades after color sorting is 15.3, 55.7, 94.1, 90.2, and 146.4 ppb, respectively. The aflatoxin in OS grade is predicted from equation 7 to be 175.3 ppb.

Summary and Conclusions

When sorting farmers' stock peanuts by size only (no color sorting), the aflatoxin concentration is lower in the larger jumbo (J) and medium (M) grades and higher in the N1, OE, SS, and OS grades than among all kernels in the farmers' stock lot before sorting by size. Sorting by size was beneficial in concentrating aflatoxin especially in the poorer quality OE and OS grades. The aflatoxin concentration in each of the six grade sizes before color sorting was correlated with the aflatoxin among all kernels in the farmers' stock lot. Equations were developed for each grade to predict the aflatoxin concentration in a given grade (before color sorting) knowing the aflatoxin in the farmers' stock lot.

Color sorting kernels in each grade into accept and reject categories was an effective method to concentrate contaminated kernels into the reject category. Except for kernels in the SS grade, the aflatoxin concentration among kernels in the accept category was typically 30 to 60% less than the aflatoxin concentration among all kernels in a grade size before color sorting. For a given grade, the aflatoxin concentration in the accept category was correlated with the aflatoxin concentration among all kernels in the grade before color sorting. Equations were developed for each grade to predict the aflatoxin concentration in the accept portion knowing the aflatoxin in all kernels in the grade.

Because of the relationships between aflatoxin in the mini-lot and aflatoxin in a given grade before color sorting and aflatoxin in the accept portion of a specific grade after color sorting, equations were developed to predict the aflatoxin concentration in the accepted portion of a given grade knowing the aflatoxin concentration in the farmers' stock lot. These prediction equations can possibly be used by the sheller as a management tool to predict the potential for reducing the aflatoxin concentration in the acceptable portion of certain grades of shelled peanuts after color sorting by estimating the aflatoxin concentration in the farmers' stock peanuts. These prediction equations should also help the USDA and the peanut industry define accept/reject limits for aflatoxin sampling plans developed for farmers' stock peanuts.

The prediction equations are probably dependent in part on the maturity of the crop and the calibration of the color sorters. However, the prediction equations developed in this study, may help the peanut industry to predict how sorting by size and color will partition aflatoxin in farmers' stock lots into various shelled peanut grades in future crops.

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