dust and tractive forces during grain loading and unloading, the tube would be useful to provide protection for the highly sensitive equipment and might also have acoustical advantages.

The tube trap greatly increased the detection as long as the number of beetles was small and even one beetle in the trap caused strong signals. At a later stage of infestation, the trap function was negligible, with still high numbers of signals after removal of beetles from the trap.

The calculated number of beetles for the experiments was important to get an impression about the population size and the differences between the two experiments. Since the program was not developed for experiments like the one described above, there is an important flaw. While it is possible to enter the number of beetles at the start of the experiment as a basis for the population, it is not possible to subtract the number of beetles removed from the trap. Especially in the first weeks of the experiment with only 200 adult beetles in the box, even small numbers of removed beetles will alter the size of the developing population. Therefore, the population size given in the results is likely to be overestimated.

The results indicated that the described acoustic system might be a suitable method for early detection of insects in storages. In a next step, the developed "Beetle Sound Tubes" will be installed in silos and tested with automatic signal detection software to provide farmers and storekeepers with detailed information about infestation and possible treatment.

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Controlling insects in stored grain by disturbing the grain

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Abstract

Insects can cause damage to stored grain, especially on smallholder farms in the tropics. *Sitophilus zeamais* (maize weevil, MW) and *Rhyzopertha dominica* (lesser grain borer, LGB) are often involved. Our objective was to determine, by four experiments, if physical disturbance of grain can control these pests. In Experiment 1, 2.6-L unsealed recycled coffee cans were each loaded with 1 kg of maize and 25 live adult MW/kg. Every 12 h, disturbed treatment cans were manually rolled through one circumference. After 160 d, live MW numbers had been reduced by 93% compared to undisturbed cans. In Experiment 2, MW-infested maize was placed in 20-L plastic cans and stored by farmers in Tanzania. Each farmer had three cans. Two were disturbed by shaking morning and evening and the third was left undisturbed. After 90 d, MW populations had increased in the undisturbed containers, but had decreased to zero in every disturbed container. In Experiments 3 (and 4), maize (wheat) infested with 25 adult MW/kg (LGB/kg) was placed in six boxes. Three of the boxes were disturbed every 12 h by use of Sukup motor-driven grain stirrers; the other three were undisturbed. After 120 days, MW numbers in undisturbed boxes had increased, but were zero in stirred boxes. In Experiment 4, 80-d samples showed increased numbers of LGB in undisturbed boxes but reductions of over 98% in stirred boxes. Quality of disturbed grain was similar or better than that of undisturbed grain. This work suggests that grain disturbance may be an effective non-chemical, non-hermetic physical approach for control of stored grain insects.

Keywords: maize, wheat, maize weevil, lesser grain borer, grain disturbance, postharvest loss

1. Introduction

About 70 million Mg of maize and 25 million Mg of wheat are grown in Africa each year (FAOSTAT, 2014; USDA, 2018). Postharvest dryweight losses for maize and wheat in Africa for 2016 are estimated at 18.8 and 13.6%, respectively (APHLIS, 2018). Without proper management, losses for an individual producer can reach 100%. A large contributor to the postharvest loss in maize is *Sitophilus zeamais*, the maize weevil (MW). Female maize weevils deposit eggs in holes bored into the grain and seal each hole with a protective gelatinous plug (Danho et al., 2015). Upon hatching, larvae feed on the endosperm of the kernel, and leave as adults through an exit hole. Maize weevils will over time totally destroy stored maize. One of the main contributors to postharvest loss in wheat is *Rhyzopertha dominica*, the lesser grain borer (LGB) (Government of Canada, 2013). Female grain borers deposit up to 500 eggs loosely onto kernels of grain and the egg stage lasts about 32 days. Larvae then eat into the wheat kernels where they complete their development. Adults emerge by chewing through the outer grain layers and can live up to 240 days (Akol et al., 2011). LGBs feed on the grain and leave behind empty husks and flour. Hermetic storage and use of insecticides are effective approaches to prevent or control insects in grain stored on smallholder farms, but each has their issues. Maintaining hermetic conditions in a container is difficult. Purchase of insecticides is a troubling recurring cost, toxic effects to people are possible due to misuse or residue, insect resistance can develop, effective insecticides may not be available, and fumigants may have environmental effects. Another approach that can be effective for smallholder farmers and others is physical disturbance that is an action such as tumbling or stirring that causes kernels to change position. This disturbance does not involve use of chemicals and it can be accomplished many different ways. Quentin et al. (1991), working with common beans infested with the common bean weevil, *Acanthoscelides obtectus* (Say), investigated the effect of disturbance by bean tumbling to control these storage insects. They hypothesized that when beans are physically disturbed numerous times, weevil larvae die due to exhaustion before gaining access to the cotyledon. The experiment consisted of tumbling storage containers loaded with beans and bean weevils every eight hours. A 95% or greater overall mean reduction in bean weevil population was achieved due to storage container physical disturbance. This paper describes four experiments carried out with the objective of determining the effectiveness of disturbance for control of maize weevils in stored maize and for control of lesser grain borers in wheat. Grain quality parameters (moisture content, fine material and test weight) were measured as part of each of the experiments, but only insect mortality is discussed in this paper.

2. Materials and Methods

Experiment 1 Materials and Methods

Recycled 2.6-L plastic ground coffee containers were used to hold the maize and weevils (Fig. 1). The containers had two internal baffles at approximately 120^0 apart as part of the container design. A third 1.5-x-1.5 x 10-cm wood baffle was affixed in by means of screws to ensure thoroughly mixing. One 10-cm diameter round hole was cut through each lid and screen was glued over the holes with silicon glue to allow air circulation while preventing escape of weevils. The lids with screens were held on the containers by two rubber bands per container. Commercial comingled bulk maize used in the experiment was purchased from West Central Coop Elevator (1095 T Ave, Boone, IA 50036).

Fig. 1. Experimental containers for Experiment 1 (Bbosa et al., 2014).

Each plastic container was loaded with 1.00 kg of 13.6% (w.b.) moisture maize that left approximately a quarter of the container volume unoccupied for thorough mixing while being turned. Maize weevils for this experiment *(S. zeamais)* were obtained from a supply maintained in maize of 10-14% (w.b.) moisture content at 27°C by the Department of Agricultural and Biosystems Engineering at Iowa State University. The experiment consisted of two treatments: undisturbed (control) containers and disturbed containers with three replications of each container, and four different storage times (40, 80, 120 and 160 days), totaling 2x3x4=24 containers. Twenty five live unsexed adult weevils were loaded into each of the containers, which were then randomly laid longitudinally in a chamber maintained at 27^0C. Humidity was not controlled in the chamber. Every 12 h, the disturbed treatment containers were manually rolled through one circumference (15.6 cm diameter or 49 cm). At 40, 80, 120 and 160 d, three undisturbed (control) containers and three disturbed containers were picked randomly from the experimental chamber for data collection. Weevil mortality and grain quality parameters were determined. A two-way ANOVA was performed and Tukey's means comparison was used to detect statistical significance in treatments at $\alpha=0.05$ using JMP Pro 10.

Experiment 2 Methods and Materials

Experiment 2 was conducted over a three months period in three maize-producing regions (Manyara, Dodoma and Morogoro) of Tanzania. For each region, one major maize-producing district was selected. Then one ward was selected and from each ward, and three small-holder maize farmers were randomly chosen. Each farmer was given twelve plastic containers—nine for treatments and three for control. The study consisted of two treatments: disturbed and control. A total of 108 clean 20-L plastic containers (36 per region) were used. Each container was loaded with 10 kg of fresh white maize and 0.50 kg of white maize infested with mixed-aged adult *S. zeamais*. The initial numbers of *S. zeamais* were determined (Tab. 1). The disturbed containers were disturbed twice a day (12 hours apart), whereas the control containers were not disturbed until the end of the study. At the end of each storage time (30, 60 and 90 days), three treatment containers and one control from each farmer were randomly opened and the number of live and dead *S. zeamais* were determined. Data collected were analyzed using the Statistical Analysis System (SAS) software using $\alpha = 0.05$.

Tab. 1 Initial numbers of *S. zeamais* in each region per 0.5 kg of infested maize for Experiment 2 (Suleiman et al., 2016).

Storage Time (days)	Dodoma		Morogoro		Manyara	
	Control	Disturbed	Control	Disturbed	Control	Disturbed
30	89	53	28	21	75	30
60	52	54	25	27	73	41
90	74	51	23	20	120	86

Experiments 3 & 4 Materials and Methods

These two experiments used the same equipment and procedure. Grain infested with 25 insects/kg was loaded in six 104 cm x 13 cm x 76 cm boxes in a 27^{0}C laboratory. Experiment 3 used maize and maize weevils; Experiment 4 used wheat and lesser grain borers. Three of the boxes in each experiment were disturbed by use of commercial Sukup electric motor-driven grain stirrers, i.e., one stirrer per box (Sukup Manufacturing Co., 2014) every 12 hours; the other three control boxes in each experiment were left undisturbed. Every 40 days, all the boxes were sampled using a grain probe.

Samples were analyzed for presence of live insects and for grain quality parameters.

3. Results

Experiment 1 Results

At 40 d, the live maize weevil mean declined from 25 to 11±1 in the undisturbed, and to 6±3 in the disturbed treatment, however this difference between treatments was not statistically significant (Tab. 2). By 80 d, the undisturbed population rebounded to 15±2, while the disturbed population dropped further to 1±2, where it remained through 120 d. The disturbed treatment population reached 3±2 at 160 d. It is unclear whether this slowly increasing trend would continue if the maize were stored longer. For 120 and 160 d storage periods, undisturbed containers showed a continued increase in the number of live weevils whereas in the disturbed containers numbers remained low. Live weevil means were not significantly different at 0 and 40 d between treatments but were significantly higher for the undisturbed treatment at 80 (p=0.0016), 120 (p=0.0030) and 160 d (p=0.0006). After 160 days, live weevil means in the disturbed containers were 7% of those in the undisturbed containers. An analysis of the results with time was also done for each treatment (Tab. 2). In the undisturbed treatment, there were no significant differences between 0, 40 and 80 days. Live weevil means were not significantly different between 120 and 160 days, but these values were significantly higher than those for 0, 40 and 80 days. The live weevil means in the disturbed treatment were significantly lower at all times after 0 day.

Tab. 2 Comparison of means of live weevils over time for disturbed versus undisturbed (control) treatments for Experiment 1 (Bbosa et al., 2014).

		Storage Time (days)				
Item	**Treatment**	**0**	**40**	**80**	**120**	**160**
Number of live weevils/kg	Undisturbed	$25±0^{Ab}$	$11±1^{Ab}$	$15±2^{Ab}$	$40±8^{Aa}$	$44±5^{Aa}$
	Disturbed	$25±0^{Aa}$	$6±3^{Ab}$	$1±2^{Bb}$	$1±2^{Bb}$	$3±2^{Bb}$

Each value within the table is the mean ± standard deviation of three replicates. Means not followed by the same upper case letter between treatments or not followed by the same lower case letter within each treatment indicate significant difference at the 0.05 level.

Experiment 2 Results

Tab. 3 shows the number of live insects throughout the study. For all control containers, insect numbers increased significantly between 30 and 60 days, and between 60 and 90 days. For the disturbed containers, there were no live weevils in any containers in any region after 90 days. Weevil numbers did not decrease significantly after 30 days in any region except Dodoma.

Tab 3. Number of live *S. zeamais* in maize for Experiment 2 (Suleiman et al., 2016).

Storage Time (days)	Control containers			Disturbed containers		
	Dodoma	Morogoro	Manyara	Dodoma	Morogoro	Manyara
30	20 ± 8^{c}	9 ± 2^{c}	12 ± 4^{c}	10 ± 2^{a}	2 ± 1^{a}	3 ± 1^{a}
60	68 ± 31^{b}	49 ± 35^{b}	77 ± 44^{b}	2 ± 1^{b}	5 ± 1^{a}	0 ± 0^{a}
90	109 ± 22^{a}	119 ± 35^{b}	152 ± 36^{a}	0 ± 0^{b}	0 ± 0^{a}	0 ± 0^{a}

Each value within the table is the mean ± standard deviation of three replicates. Means not followed by the same lower case letter in each column indicate significant difference at the 0.05 level.

Experiment 3 Results

After 40 days, live MW population means in unstirred control boxes decreased significantly to 1.7 per kg of maize but then rebounded significantly to 18 after 80 days (Tab. 4). No live MW were found in any of the stirred box samples after 40 or after 80 days. The experiment was terminated after 80 days. Stirring greatly reduced or eliminated maize weevils in the stirred boxes.

Experiment 4 Results

The 40-day samples of wheat from the three control boxes all contained multiple LGB, while there was a total of one LGB in the stirred box samples (Tab. 5). The mean of the control group was significantly greater than that of the stirring treatment. At 80 days, stirring was stopped and the stirred boxes were undisturbed for the next 40 days to see if eggs and larvae would emerge as adults. There were not significant differences found between the stirred and control treatments, although control box means are far higher than stirred box means. This is presumably because of the high standard deviations among the control replicates at both 80 and 120 days. Further analysis of these data is underway. Discarding of one or two outlier data points may be justified and may result in significant differences between treatments at 80 and 120 days.

4. Discussion

Assuming further analysis concludes there are significant differences between treatments after 80 days for Experiment 4, there is evidence from these four experiments that disturbance is effective in controlling maize weevil in stored maize and lesser grain borer in stored wheat. Further research will be needed to determine how disturbance can be carried out in larger grain containers. One untested possibility is to use grain stirring machines in conventional steel grain bins to carry out disturbance.

Tab. 4 Means comparison of live weevils for stirred versus unstirred (control) containers in Experiment 3 (Rau et al., 2018).

Item	Treatment	T=0 d	T=40 d	T=80 d
Number of live weevils per kg maize	Control	25 ± 0^{Aa}	1.7 ± 0.6^{Ab}	18 ± 4.0^{Ac}
	Stirred	25 ± 0^{Aa}	0 ± 0^{Ba}	0 ± 0^{Ba}

Each value within the table is the mean ± standard deviation of three replicates. Means not followed by the same upper case letter between treatments or not followed by the same lower case letter within each treatment indicate significant difference at the 0.05 level.

Tab. 5 Comparison of means of live lesser grain borers over time for disturbed versus undisturbed wheat in Experiment 4.

Item	Treatment	T=0 days	T=40 days	T=80 days	T=120 days
Number of live lesser grain borers/kg	Control	25 ± 0^{Aa}	11 ± 2.5^{Aa}	131 ± 110^{Aa}	91 ± 99^{Aa}
	Stirred	25 ± 0^{Aa}	1 ± 1.6^{Bc}	2 ± 1.7^{Ac}	8 ± 1.7^{Ab}

Each value within the table is the mean ± standard deviation of three replicates. Means not followed by the same upper case letter between treatments or not followed by the same lower case letter within each treatment indicate significant difference at the 0.05 level.

This technology is currently available. In all four experiments, quality of disturbed grain was similar or better than that of grain in undisturbed containers, except fine material in the stirred boxes which was higher than in the undisturbed boxes. In three of the experiments, we observed a drop in live insects from initial numbers in the control containers during the initial storage periods. Bbosa et al. (2014) also observed this decrease in an experiment with steel barrels. This decrease probably happens because some adult weevils die before adult weevils from eggs deposited in this new environment begin to emerge. All of these experiments employed a 12-hour disturbance interval, although we did not have a solid reason for choosing this interval. Quentin et al. (1991) found an eight-hour interval to be effective for control of bean weevils in stored beans. Additional research is needed to understand why disturbance is effective and to identify an optimum disturbance interval.

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