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Evaluation of different temperature management strategies for suppression of *Sitophilus zeamais* (Motschulsky) in stored maize

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Abstract

Three years of experimental trials (2001–2003) were conducted in 12.7 t capacity pilot-scale bins to determine the survival, reproduction and suppression of *Sitophilus zeamais* Motschulsky under three temperature management strategies, no aeration (NA, control), ambient aeration (AA, $\leqslant$23.9 °C), and chilled aeration (CA, $\leqslant$18.3 °C) from May to November in Indiana, USA. One-way ANOVA indicated that the number of progeny for small adult populations of caged insects (0.14–0.28 insects per gram maize) embedded 0.6 m deep in the stored grain mass varied among temperature strategies for some, but not all of the storage periods. Progeny numbers in the CA strategy were significantly lower ($P<0.05$) than those for the NA and AA strategies for periods with longer hours of grain temperature $\leqslant$15.0 °C. There were no differences in progeny numbers between the NA and AA strategies for most of the storage periods. This may have been due to higher mortality, lower oviposition and fecundity from overcrowding of *S. zeamais* under the NA strategy caused by factors in the caged insect microclimate (e.g., rapid food depletion, heating, moisture, molding, and high CO_2 levels). Our results suggest that maintaining stored maize at temperatures $\leqslant$15.0 °C for longer periods suppressed *S. zeamais* progeny more effectively than at $\leqslant$18.3 °C. In addition, leaving the stored grain bulk unaerated early in the spring so it remained cool at $\leqslant$15.0 °C due to winter aeration resulted in early suppression of *S. zeamais* progeny.

Keywords: *Sitophilus zeamais*; Maize; Temperature control; Ambient aeration; Chilled aeration

1. Introduction

Maize, commonly known as corn in the United States, is an important commodity grown in the Midwestern United States and can be infested and damaged by a variety of internally and externally feeding insect species while in storage (Arbogast and Throne, 1997). *Sitophilus zeamais* is one of the primary insect pests of maize in the South and Midwestern United States, and an internal feeder whose adults attack whole kernels and whose larvae feed and develop entirely within kernels (Storey, 1987). Traditionally, control of stored-insect pests has been achieved primarily through the use of residual pesticides and fumigation. The 1996 Food Quality Protection Act (FQPA) (US EPA, 1996) passed by the US Congress set stringent health-based safety standards for pesticide residues in foods. In addition, major pest species have developed resistance to a number of the target organophosphate (OP) pesticides affected by the FQPA. Insect pest resistance to malathion (Subramanyam and Hagstrum, 1995; Arthur, 1996), chlorpyrifos-methyl (Subramanyam and Hagstrum, 1995), chlorpyrifos-methyl and dichlorvos (Zettler, 1991), and pirimiphos-methyl (Beeman and Wright, 1990) are well documented.

Stored-product pests are primarily thermophilic in nature, i.e., their growth and survivability is greatly influenced by temperature. The lower developmental threshold for most stored-product pests is approximately 18 °C (64.4 °F) (Howe, 1965). The optimum developmental range of many stored-grain insect pests is approximately 25–35 °C (77–95 °F) (Fields, 1992). For most species there is a range of temperatures covering some 3–4 °C at which the rate of increase is greatest, usually at a humidity of

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60% or more (Howe, 1965). Low temperatures are of greater significance. For every species there is a minimum constant temperature threshold below which development ceases and for many there is also a low humidity that is lethal.

Cooling stored grains through low-volume aeration (0.05–0.1 m^3/min/t) to limit insect pest development is an important component of management plans in Midwestern (Cuperus et al., 1986, 1990) and North Central United States (Gardner et al., 1988). The use of aeration to reduce the grain bulk temperature to below optimum development thresholds of stored-product insect pests is an IPM-based approach to manage insects in bulk grains (Hagstrum et al., 1999). Maier et al. (1996) used a simulation model to evaluate temperature management of *S. zeamais* in stored maize in three locations in the United States. They showed that *S. zeamais* and dry matter loss (DML) can be effectively controlled using chilled aeration (CA) in the fall with summer re-chilling, but no aeration (NA) was found to be ineffective and undesirable for the control of *S. zeamais* and DML. In another simulation study on the feasibility of aeration management of *S. zeamais* populations in maize stored in the Southern and Northern United States using recorded weather data, Arthur et al. (1998, 2001) showed that aeration dramatically reduced the predicted number of *S. zeamais* in all geographical zones compared to population levels in unaerated corn.

In order to validate these simulation studies, reliable field data on *S. zeamais* population growth in stored corn under different temperature regimes, especially during the peak infestations period (spring–summer) is essential. Montross (1999) conducted studies on the effects of NA, ambient aeration (AA) and CA management strategies on the control of caged populations of *S. zeamais*, red flour beetle, *Tribolium castanaeum* (Herbst) and Indian meal moth, *Plodia interpunctella* (Hübner) in 12.7 t capacity pilot bins in the summers of 1998 and 1999. He used his data to validate a comprehensive stored grain ecosystems model; the post-harvest aeration and storage simulation tool (PHAST). The insect population mortality (adults and their progeny) over the experimental period was higher in the CA and AA bins compared to the unaerated bins. However extensive analysis of his data was not conducted. The use of high airflow aeration (1.0–3.0 m^3/min/t) to take advantage of brief cool weather periods in the summer has been studied (unpublished) and could be utilized strategically and economically to suppress insect pest development in stored maize.

In order to effectively implement temperature management methods for the *S. zeamais* in stored maize during the most vulnerable period with high stored-pest pressures (spring–fall), it is necessary to have a good understanding of their survival and reproduction under a range of temperature management strategies. These data will be useful in validating models to predict *S. zeamais* population growth under various temperature management strategies. Thus, the primary objective of this study was to evaluate three different temperature management strategies: NA (control), AA, $\leqslant$23.9 °C, and CA, $\leqslant$18.3 °C for the suppression of *S. zeamais* in stored maize.

2. Materials and methods

2.1. Stored maize

The maize used was harvested in the fall of 1999 at 17.8% moisture (wet basis), binned in 12.7 t capacity pilot bins and dried to 14% with natural air. Each bin was filled with about 9.2 t of yellow-shelled maize. The corn was maintained through the spring of 2000 using AA, but was fumigated once in September 2000 before the beginning of the first year experimental trials (Trial 1). For the NA strategy, 3 bins were used and 4 bins each were used for both the AA and CA strategies, respectively.

2.2. Temperature management strategies

From June 2001 to October 2001, three aeration management strategies (NA, AA and CA) were implemented in the first phase (Trial 1) of the experiment. The bins were maintained at temperatures below 5 °C through the winter period of 2001, after which the second phase of the experiment (Trial 2) was implemented from May 2002 to October 2002. The third phase of the experiment was conducted from June to November 2003 (Trial 3), following winter cooling of the grain below 5 °C.

For the NA management strategy, we removed the fans from the bins and sealed the ducts with a wooden board to prevent the entry of upward drafts of air current from the plenum through the grain due to wind. For the AA strategy, a computer-based controller, OPIGIMAC (OPIsystem, 2002) was set to turn fans (0.75 hp) on based on a maximum grain temperature of 23.9 °C (75 °F) and off at a minimum grain temperature of 15.6 °C (60 °F) in order to maintain a target grain temperature of 21.1 °C (70 °F). The airflow rate delivered by the fans through the grain was 2.9 m^3/min/t (2.6 cfm/bu). For the CA strategy, a computer-based controller, OPIGIMAC (OPIsystem, 2002) was set to turn on a chiller ducted to 4 bins based on a maximum grain temperature of 18.3 °C (65 °F) and off at a minimum grain temperature of 10 °C (50 °F) in order to maintain a target grain temperature of 15.6 °C (60 °F). The chiller provided an airflow rate of approximately 1.3 m^3/min/t (1.2 cfm/bu) and varied depending on the ambient conditions. The grain temperature for Sensor 3 (1.5 m from the bin floor, 0.6 m from the grain surface and 0.3 m from the bin wall) on the south cable of the bin with the least shade (west-most bin) out of the 4 ducted bins was used as the reference temperature for the chiller control. The thermistor on that cable generally reached the highest temperature among all cables in this set of ducted bins.

The grain mass and headspace temperatures at each cage location were monitored with 26 thermistors on temperature cables, one at the center and four cables at the four

cardinal directions 0.3 m from the bin wall. Temperature data were logged at 1 h intervals by the OPIGIMAC (OPIsystem, 2002) data acquisition system. Temperature data used for the analysis were from sensors located in the cage location at about 0.6 m (2 ft) from the grain surface. A weather station located on the test site logged data of ambient air temperature and relative humidity.

2.3. Insect bioassay cages

Adult *S. zeamais* confined in cages and embedded in the stored corn mass were used to measure the efficacy of the three different temperature management strategies for a storage period of 4 months for Trial 1 in 2001, and 5 months for both Trials 2 and 3 in 2002 and 2003, respectively. Cages were made from PVC pipe that was 5.1 cm (2 in) in diameter and 10.2 cm (4 in) long. They were filled with whole maize and broken kernels for diet, obtained from the stored maize bulk, and closed at both ends with a 0.4 mm monofilament mesh to keep the insects from escaping, while allowing airflow through them when installed in the upright position. Maize kernels for the diet were frozen at about −10 °C for a week to kill any insects before use. Each cage contained 180 g kernels at 14.0% moisture with 50 unsexed adults (0.28 insect per gram of grain) in Trials 1 and 2, but was reduced to 25 unsexed adults (0.14 insect per gram of grain) in Trial 3 due to the observation of overcrowding that might have caused early diet depletion and mortality from heat of respiration in the nonaerated bins in Trials 1 and 2. In Trial 1 (2001), a set of four cages was buried 0.3 m from the south wall. One cage was removed monthly from this location from June to September to count dead and live insects. In Trial 2 (2002) and Trial 3 (2003), a cage was buried in each of five locations; at the center and four cardinal directions about 0.3 m from the bin wall. One cage was removed monthly from a different location chosen at random from June to October for Trial 2, and July–November for Trial 3 to count dead and live insects. The location from which a set of cages was pulled out every month was determined using a randomized block design, with the group of bins for a temperature management strategy as a block. Within each block, the cage pullout months were assigned at random to the cage locations in the bins.

2.4. Sampling insect bioassay cages for progeny number

For all cages pulled out monthly, a count for dead and live insects was conducted. After the initial insect count of *S. zeamais*, the cage content (grain material only) was divided into halves and put in 100 mL double layer plastic cups with tightly secured lids. Every 3 days, the cup contents were sieved and emerged progeny was counted until the 60th day from the date of cage removal from the bins. It was estimated that monitoring emergence until the 60th day after the cages were pulled out was enough time for any egg that was oviposited when the cages were in the bin to develop into an adult. The effectiveness of the various temperature control strategies was determined from the progeny number calculated as the total insect count (initial dead and live adults when cage was pulled out plus progeny number to the 60th day) minus the initial insect count (50 for Trials 1 and 2, and 25 for Trial 3). This gives a measure of the population increase from its initial number. Data from bin replicates for each strategy were averaged to determine the mean numbers for that treatment (strategy).

2.5. Impact of temperature management strategies on *S. zeamais* survival, reproduction and control

Data of number of progeny produced by caged insects held in the stored corn mass were subjected to one-way single factor analysis of variance (ANOVA) using the PROC GLM procedure (SAS, 2001) to determine differences in *S. zeamais* progeny numbers (at $\alpha = 0.05$) among the three temperature strategies. Fisher's protected least significant difference (LSD) procedure was used to determine differences in the *S. zeamais* progeny numbers between temperature strategies at $\alpha = 0.05$ level (SAS, 2001). The temperature profiles during the storage periods in 2001–2003 were plotted for the three management strategies using MS Excel (Microsoft Excel Analysis ToolPak; Microsoft, 2003).

3. Results

3.1. Temperature profiles in the stored bulk for the three management strategies

Figs. 1(a)–(c) show the grain temperature profiles during the experimental trial periods (May–November) in 2001–2003, respectively, for the three temperature management strategies. At the end of every trial, the grain temperature in all bin replicates was reduced to below 5 °C using AA during the winter period (November–April). The temperature profile for a single bin was the average of the temperature profiles of the sensor on the cable located 0.6 m (2 ft) below the grain surface for the five cables. The temperature profile for a temperature management strategy was the average of the temperature profiles of the bin replicates.

The temperatures for the CA strategy were below 18.3 °C, the set maximum, 95% of the time on average during the experimental periods in all 3 years. However, there were two periods in 2001 and 2003 that the temperature rose above 18.3 °C due to shutdown of the chiller because of power failure and/or repairs. For the AA bins, the temperature profiles in the stored maize for all 3 years were mostly below the set point maximum of 23.9 °C during the period prior to July and after September. This was because ambient temperatures were favorable for aeration to maintain temperatures below this maximum threshold. Temperatures rose above this maximum threshold in the peak of the

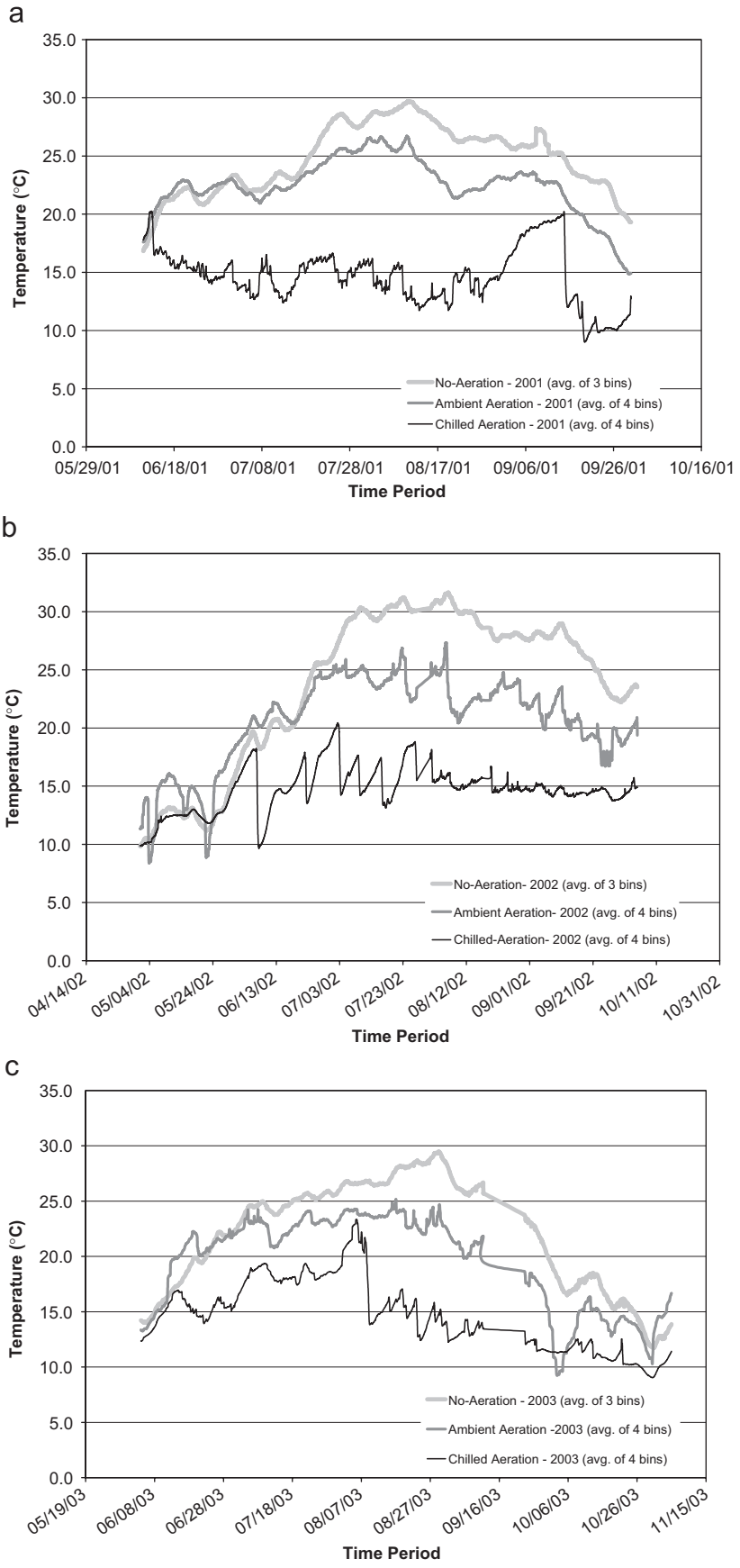

Fig. 1. Average maize temperature profiles at the location of the insect cages buried 0.6 m deep in the stored grain mass during the (a) 2001, (b) 2002 and (c) 2003 trials.

Table 1
Analysis of variance results showing progeny numbers (mean ± SE)[a] per month for *S. zeamais* adults under the three aeration management strategies (2001 Trial)

Month	Treatments, mean ± SE[a]			R^2	CV	*F*-Value[b]	Pr > *F*
	NA[c]	AA[d]	CA[e]				
1	111.3 ± 73.4a	48.7 ± 4.7a	49.3 ± 20.7a	0.40	63.2	2.0	0.22
2	97.0 ± 25.1a	199.8 ± 42.0b	88.0 ± 77.2a	0.55	42.1	4.9	0.04
3	307.7 ± 232.0a	331.8 ± 48.0a	64.0 ± 54.5b	0.58	54.5	5.5	0.03
4	314.0 ± 40.5a	448.0 ± 216.2a	69.8 ± 28.7b	0.67	49.3	8.0	0.01

[a]The same letters in a row indicate that progeny numbers were not significantly different using Fisher's protected least significant difference (LSD) multiple comparison procedure ($\alpha = 0.05$) among temperature strategies for the monthly periods.
[b]Degrees of freedom for *F*-tests was 2,8 for all the months except for month 1 which was 2,6.
[c]NA is the designation for replicate bins ($n = 3$) with no-aeration treatment.
[d]AA is the designation for replicate bins ($n = 4$) with ambient-aeration treatment.
[e]CA is the designation for replicate bins ($n = 4$) with chilled-aeration treatment.

Table 2
Analysis of variance results showing progeny numbers (mean ± SE)[a] per month for *S. zeamais* adults under the three aeration management strategies (2002 Trial)

Month	Treatments, mean ± SE[a]			R^2	CV	*F*-Value[b]	Pr > *F*
	NA[c]	AA[d]	CA[e]				
1	52.7 ± 16.8a	114.8 ± 45.5a	88.5 ± 50.5a	0.31	48.1	1.8	0.22
2	219.7 ± 80.5a	293.5 ± 100.2a	84.8 ± 28.2b	0.66	38.2	7.8	0.01
3	257.3 ± 105.5a	829.8 ± 146.0b	146.0 ± 69.2a	0.91	26.4	41.8	< 0.01
4	398.0 ± 557.9a	1062.8 ± 119.6b	141.3 ± 94.6a	0.72	53.9	10.3	0.01
5	450.7 ± 533.3a	1086.0 ± 293.8b	187.5 ± 93.5a	0.66	55.8	7.9	0.01

[a]The same letters in a row indicate that progeny numbers were not significantly different using Fisher's protected least significant difference (LSD) multiple comparison procedure ($\alpha = 0.05$) among temperature strategies for the monthly periods.
[b]Degrees of freedom for *F*-tests was 2,8 for all the months.
[c]NA is the designation for replicate bins ($n = 3$) with no-aeration treatment.
[d]AA is the designation for replicate bins ($n = 4$) with ambient-aeration treatment.
[e]CA is the designation for replicate bins (n = 4) with chilled-aeration treatment.

summer (July–August) bringing the stored maize temperatures in the AA bins above 25 °C. For the NA bins, the temperature increased with the daily ambient temperatures in the spring, peaking at about 30 °C in midsummer, and subsequently decreased with decreasing low ambient temperatures in the fall. Because of the small bin diameter (2.7 m), stored grain temperatures were highly affected by ambient temperatures in the bins with NA.

3.2. Impact of temperature management strategies on *S. zeamais* survival, reproduction and suppression

Analysis of variance results showing mean progeny numbers per month for *S. zeamais* adults under the three temperature management strategies are presented in Tables 1–3 for trials in 2001–2003, respectively. In Trial 1 (Table 1), the number of progeny of *S. zeamais* varied among temperature strategies in the second, third and fourth months of storage ($P < 0.05$) but was not significantly different in the first month ($P = 0.22$). Progeny numbers for AA was significantly greater than in either the NA or CA temperature management strategy in the second month. Progeny numbers for NA and AA were significantly greater than in the CA strategy in the third and fourth month.

In Trial 2 (Table 2), the number of progeny of *S. zeamais* varied among temperature strategies in the second, third, fourth and fifth months of storage ($P < 0.05$) but was not significantly different in the first month ($P = 0.22$). Progeny numbers for the NA and AA strategies were significantly greater than for the CA strategy in the second month. However, the progeny for the AA strategy was significantly greater than for either the NA or CA strategies in the third, fourth and fifth months.

In Trial 3 (Table 3), *S. zeamais* progeny varied among temperature strategies in the first, second, and third months of storage ($P < 0.05$), but was not significantly different in the fourth ($P = 0.39$) and fifth ($P = 0.29$) months. Progeny numbers for the NA and AA strategies were greater than for the CA strategy in the first three months and similar for all three strategies in the last 2 months (months 4 and 5).

Table 3
Analysis of variance results showing progeny numbers (mean ± SE)[a] per month for *S. zeamais* adults under the three aeration management strategies (2003 Trial)

Month	Treatments, mean ± SE[a]			R^2	CV	*F*-Value[b]	Pr > *F*
	NA[c]	AA[d]	CA[e]				
1	628.7 ± 149.1a	709.0 ± 182.0a	265.8 ± 99.7b	0.72	28.0	10.05	0.01
2	1149.7 ± 206.7a	1141.8 ± 190.7a	625.3 ± 202.1b	0.67	20.1	7.19	0.02
3	1029.0 ± 308.3a	1312.0 ± 93.5a	434.8 ± 257.9b	0.78	27.5	12.2	0.01
4	912.3 ± 380.9a	1119.5 ± 694.7a	618.0 ± 235.6a	0.21	55.4	1.07	0.39
5	667.7 ± 21.7a	1126.8 ± 711.0a	639.3 ± 166.7a	0.26	54.3	1.44	0.29

[a]The same letters in a row indicate that progeny numbers were not significantly different using Fisher's protected least significant difference (LSD) multiple comparison procedure ($\alpha = 0.05$) among temperature strategies for the monthly periods.
[b]Degrees of freedom for *F*-tests was 2,7 for months 2 and 3, and 2,8 for months 1, 4 and 5.
[c]NA is the designation for replicate bins ($n = 3$) with no-aeration treatment.
[d]AA is the designation for replicate bins ($n = 4$) with ambient-aeration treatment.
[e]CA is the designation for replicate bins ($n = 4$) with chilled-aeration treatment.

Table 4
Average number of hours that the temperature, $T \leqslant 15.0\,^{\circ}C$ at the cage locations ($n = 5$ temperature sensors/bin replicate) for the three aeration strategies for the total storage period

Trial year	Hours (h) at temperatures $\leqslant 15.0\,^{\circ}C$			Total storage hours
	NA	AA	CA	
2001	0 (0%)[a]	19 (1%)	1535 (57%)	2674
2002	682 (19%)	427 (12%)	3384 (95%)	3573
2003	479 (14%)	852 (24%)	2950 (85%)	3488

[a]Percentage of total storage hours for the entire experimental period.

4. Discussion

Cooling the grain mass with ambient air to $\leqslant 15.0\,^{\circ}C$ for a total of 120 h with an airflow aeration rate of 0.0013 $m^3/s/m^3$ has been suggested as a method of suppressing *S. zeamais* development (McCune et al., 1963; Noyes et al., 1987), and has been demonstrated by computer simulation experiments (Arthur et al., 1998, 2001; Maier et al., 1996; Montross, 1999). Therefore, the efficacy of the three temperature management strategies could be evaluated based on the number of hours the stored grain bulk at the cage location was $\leqslant 15.0\,^{\circ}C$ for the storage period. Table 4 shows that the grain bulk subjected to the CA strategy was $\leqslant 15.0\,^{\circ}C$ much longer (1535, 3384 and 2950 h for 2001–2003, respectively) than for the AA strategy (19, 427 and 852 h in 2001–2003, respectively) and for the NA strategy (0, 682 and 479 h in 2001–2003, respectively). This resulted in less *S. zeamais* progeny under the CA strategy than under either the NA or AA strategies in all 3 years of the trials.

The AA strategy that had a maximum temperature threshold of $\leqslant 23.9\,^{\circ}C$ did not effectively control maize progeny development in the cages. Grain temperatures for the AA strategy were $\leqslant 18.3\,^{\circ}C$, the target temperature, for 160 h in 2001, 812 h in 2002 and 1329 h in 2003 compared to 30 h in 2001, 798 h in 2002 and 1185 h in 2003 for the NA strategy. Progeny produced under the AA strategy was not significantly different than under the NA strategy in all five storage months in 2003 and for three of the four storage months in 2001 (Tables 1 and 3). In the 2002 trials, progeny under the AA strategy were significantly more numerous than under the NA strategy in the last 3 months. This can be explained by examining the grain temperatures in the first month of the 2002 trial (Table 5), which had 681 h of $\leqslant 15.0\,^{\circ}C$ for grain under the NA strategy compared to 427 h for the AA strategy.

The stored grain under the NA strategy had more hours of cool temperatures $\leqslant 15.0\,^{\circ}C$ in the first month due to the winter aeration in the previous season that would have suppressed early reproductive activity. Grain is a good insulator and will keep cool for long periods of time when aerated to very low temperatures. In simulation studies by Maier et al. (2002) using the post-harvest aeration and storage simulation tool-finite element model (PHAST-FEM) described by Montross et al. (2002a, b), a 18.2 m (60 ft) diameter by 36.5 m (120 ft) height concrete silo filled with stored maize under Indiana weather conditions had most of the bulk at $\leqslant 18.0\,^{\circ}C$ up until August after cooling to 15 °C in January. In our field experiments, the grain in the relatively small steel bins (2.7 m diameter by 3 m height) with NA could not maintain cool temperatures for a long period as the weather warmed up in the summer. This suggests that grain cooled during winter aeration, especially in large diameter bins, will be able to hold relatively

Table 5
Average number of hours that the temperature, $T \leqslant 15.0\,^{\circ}C$ at the cage locations ($n = 5$ temperature sensors/bin replicate) for the three aeration strategies in the first month of storage

Trial year	Hours (h) at temperatures $\leqslant 15.0\,^{\circ}C$			Total hours	Period
	NA	AA	CA		
2001	0 (0%)[a]	0 (0%)	131 (28%)	474	06/11–06/30
2002	682 (92%)	427 (58%)	704 (95%)	740	05/01–05/31
2003	90 (14%)	103 (16%)	274 (43%)	635	06/04–06/30

[a]Percentage of total hours for the first month only.

cool temperatures into the summer season, and that re-warming grain in the spring to raise its temperature close to the average ambient temperature might not be advantageous with respect to stored pest management and suppression.

Progeny numbers produced under the NA strategy were not consistently greater than for the AA strategy as would have been expected, especially since there were more hours of temperatures $\leqslant 18.3\,^{\circ}C$ for the AA strategy than for the NA strategy. This is because *S. zeamais* progeny development was also affected by the availability of food, insect density and poor microclimate in the small cage due to high infestation levels. Hardman (1977) noted that the rate of growth of insect populations is influenced by temperature, grain moisture content, oxygen concentration, food availability and population density in the insect microclimate. Increased moisture from respiratory activity of a large insect population will promote mold growth and increase CO_2 concentration. There will also be faster depletion of food resources when more insects feed on a fixed amount of ration. This deteriorating condition can be further exacerbated when there is no air exchange in the stored grain bulk as in unaerated grain. The deteriorating microclimate limits further insect population growth and even induces insect mortality. This was most likely the scenario that occurred in the NA and AA bins. This reasoning is supported by Hardman (1977) who reported that the density of the rice weevil, *Sitophilus oryzae* (L.) held in small cells of wheat having a similar insect density per gram of wheat (0.14/g) to that in our experiment (0.14–0.28 insect per gram maize) rose to such an extent that the rates of oviposition started to decline as the insect population started to induce environmental changes. He mentioned that his results paralleled on a miniature scale the changes observed in field studies by Birch (1946), Robertson (1948) and Wilson (1946, 1949).

Another factor that caused higher progeny mortality and lower fecundity in the NA bins was poor exchange of air in the grain mass in the cage. This might explain why progeny numbers were higher in the AA strategy which had constant air exchange by aeration and thus maintained a better microclimate in the cages for progeny development than in the NA strategy. Hardman (1977) found that high weevil density coincided with high temperatures and a decline in oviposition rate which he attributed to overcrowding. Also, he stated that weevil activities such as hollowing out grains and the liberation of frass, moisture and heat encourage the explosive growth of dormant fungal populations. The multiplication of fungi will contribute to increased heat, moisture and carbon dioxide, reducing the oxygen level and food source necessary for insect survival. Lenz (1968a, b) found that while the granary weevil, *Sitophilus granarius* (L.) could survive and reproduce on several species of storage fungi—*Trichoderma* and *Penicillium* spp.—the weevil was unable to thrive on wheat infested with other species from the genera *Alternaria*, *Aspergillus* and *Penicillium*. In our studies, we observed extensive molding and clumping of the hollowed out kernels in cages under the NA strategy more than in the AA strategy, and much less than in the CA strategy. In addition, extensive diet depletion in the fourth and fifth months in all three trials was observed in the NA and AA strategies. Thus, a better microclimate condition due to intermittent aeration of the AA bins explains why the environmental conditions in replicate bins with the AA strategy were able to support more progeny development than the NA strategy in some cases.

In general, progeny numbers were greater in 2003 than in 2001 and 2002 for all three temperature management strategies. This was most likely due to a lower insect density per gram of maize (0.14) used in the cages in 2003 compared to a higher density, 0.28 used in 2001 and 2002. A lower insect density in the cage meant increased food availability as well as fecundity, given that *S. zeamais* prefer to lay one egg/kernel of grain. Therefore, it is quite critical during the design of an experiment using caged insect populations to consider all factors that might limit the rate of population growth, especially the insect density per gram of maize in the microclimate (cage).

5. Conclusions

Our work showed that chilled aeration can be used effectively to suppress *S. zeamais* progeny in stored maize by rapid cooling the grain to $\leqslant 15.0\,^{\circ}C$ during periods of warm ambient temperatures. Postponing ambient aeration (AA) of winter-cooled grain in the spring when grain is still below optimum threshold temperatures for *S. zeamais* survival will delay *S. zeamais* activity and development as the warm season approaches. This provides a better control

of *S. zeamais* progeny development through the warm summer period than early AA in the spring. Finally, experiments using caged insects in stored grain should take into consideration the potential insect densities than could build up over time in these confined spaces (microclimates) with limited food resources as was observed in our work. Lower insect densities than were used in our trials would probably have resulted in better separation of the treatments, especially between the NA and AA strategies.

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