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Temperature Management of the Maize Weevil, *Sitophilus zeamais* Motsch. (Coleoptera: Curculionidae), in Three Locations in the United States

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Abstract—A new simulation model was used to quantify the effect of eight common stored maize management practices on dry matter loss and *Sitophilus zeamais* Motsch. development using ambient weather conditions for Indianapolis, Indiana; Columbia, South Carolina; and Amarillo, Texas. For each location, good, normal, and poor storage years were identified and evaluated. No aeration was found to be ineffective and undesirable for control of dry matter loss and *S. zeamais* development in all situations. Fall-chilled aeration proved to be the most effective aeration strategy for all locations and years. However, Indianapolis showed the least benefit compared to ambient fall aeration, while Columbia benefited most. Although only continuous ambient fall aeration was investigated, the results showed that controlling the aeration process holds promise in optimizing this technique. The use of spring warm-up aeration increased the rate of quality deterioration while summer rechilling improved insect control with little increase in dry matter loss. A combination of controlled ambient aeration in the fall and chilled aeration during summer storage has significant potential as a non-chemical preventative pest management technique for all locations and years. Residual pesticides and fumigation of properly cooled maize storages should not be necessary in the United States. Copyright © 1996 Elsevier Science Ltd

Key words—aeration, grain chilling, insect control, integrated pest management

INTRODUCTION

When grains are placed into storage they are exposed to a broad range of complex ecological factors that work against the stored-grain manager's objective of maintaining grain quality. Grain temperature is among the most important because it directly affects grain quality and the development of pests. In order to evaluate the effects of weather conditions and geographic location, the Post-Harvest Aeration and Storage Trainer (PHAST) is being developed to simulate the stored grain ecosystem. It currently allows the user to evaluate alternative management

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approaches and their impact on stored maize due to *Sitophilus zeamais* Motschulsky (Coleoptera: Curculionidae) and dry matter loss from fungal respiration. Its emphasis is on teaching preventive management practices rather than solving specific storage problems, once they have occurred.

This study had the following objectives.

- Integrate a *S. zeamais* population development model into an existing aeration and storage system computer model for use on maize stored in upright steel bins (Maier, 1992).
- Refine and expand the model so it can utilize historical weather data available for various locations in the United States.
- Evaluate the effects of geographic location and management practices on development of *S. zeamais* populations and dry matter loss in shelled maize stored in three key growing regions, i.e. the midwestern (Indianapolis, IN), southeastern (Columbia, SC), and southwestern (Amarillo, TX) United States.

Environmental conditions, such as temperature and relative humidity, and grain conditions, such as temperature and moisture content, determine how fast stored product insects develop into populations large enough to threaten grain quality and value (Pedersen, 1992). When temperatures drop below 20°C, female *S. zeamais* lay few, if any, eggs (Throne, 1994). The survival rate of eggs placed under these conditions is extremely low because they are the most susceptible to changes in temperature and relative humidity. Adults are able to adapt by modifying their activity levels to changes in the environment.

Many of the fungi and insects that invade stored grain are inactive at temperatures below 10°C. At temperatures up to 35°C these pests can cause substantial damage and reduce storage life (Bailey, 1992). Temperatures below 17°C are adequate to slow insect development enough to limit pest damage (Burges and Burrell, 1964). Microbial growth can be reduced by two to five times with a temperature decrease of 10°.

The two primary objectives of aeration are to maintain a uniform temperature and keep the temperature below the limits for insect and fungal development (Noyes *et al.*, 1995). Non-uniform grain temperatures frequently result from daily and seasonal fluctuations in ambient temperature. Aeration is also used to remove unpleasant odors, vent fumigants, increase storage time of high-moisture grain, and remove heat associated with drying.

To reduce storage problems, the bin inlet conditions can also be artificially created through the use of a grain chiller. In his review, Burrell (1982) summarized one of the main uses of grain chilling as protection from insect infestation by means of cooler grain temperatures. In Michigan, stored maize was chilled repeatedly between 1988 and 1990. The results were used to establish the technical feasibility and ecological desirability of chilled aeration and storage of grain in the United States (Maier, 1992). Beginning in 1992, a United States-made grain chiller was developed jointly by Purdue University and AAG Manufacturing (Milwaukee, WI). The first trials were used to optimize the performance of the prototype chiller (Maier *et al.*, 1993). Additional research continues to determine the usefulness of chilled aeration as a non-chemical insect control method (Adams *et al.*, 1993; Maier, 1994).

Simulation of the grain storage ecosystem can be a less expensive and time-saving alternative to field research. Such a simulation model must address effects due to temperature and moisture content of grain during drying/cooling, aeration and storage, safe storage time, insect population growth, and breakdown of pesticides. Kawamoto *et al.* (1992) proposed the development of an expert system for use by agricultural extension personnel to inform local managers of the risk of pest outbreaks. The proposed expert system is being developed based on meteorological records for the Canadian prairies. Flinn and Hagstrum (1990) developed an expert system called the Stored Grain Advisor (SGA) for use by producers, elevator operators, extension specialists, and other grain managers. Rules for this expert system were developed using five simulation models for common stored-wheat pests. The SGA is capable of forecasting potential problems at the time of storage and provides a list of recommendations. Adams (1994) used an existing simulation model to develop the Post-Harvest Aeration and Storage Trainer (PHAST) to teach good grain storage management practices for any United States location. This new system model is the basis for the research presented here.

ANALYSIS AND PROCEDURE

Aeration and storage model

The in-bin aeration model is one-dimensional and is based on two non-linear partial differential equations (Parry, 1985). It assumes equilibrium conditions between the air and the grain mass. The temperature of the air and grain, the moisture content of the grain, and the humidity of the air within the pile are expressed as a function of time. The aeration model was previously verified with experimental data (Maier, 1992). Changes in grain temperature and moisture content during non-aerated storage are assumed to occur due to conduction heat transfer. An analysis of existing storage models to determine suitability for simulating cereal grain storage revealed that models using two-dimensional heat conduction appear adequate (Maier, 1992). A three-dimensional model did not appear to add sufficient accuracy to justify its use at the time (Alagusundaram *et al.*, 1990). For the purpose of analysis, the two-dimensional grain mass was divided into two separate and distinct volumes within the bin. The bulk represents 90% of the total grain volume, while the remaining 10%, referred to as the periphery, completely envelops the bulk grain.

Biological models

The loss of dry matter serves as an indicator of maize quality during storage and can be used to compare different storage environments. Thompson's (1972) approach is used to predict dry matter loss due to fungal respiration in the system model. During each time-step, the spoilage routine calculates the current multipliers for moisture content, temperature, and damage as defined by Steele *et al.* (1969), Brook (1987), and Stroshine and Yang (1990). These values are then used to calculate the equivalent reference storage time. A value of 0.5% or more is considered a large enough deterioration to lose one market grade in maize.

A *S. zeamais* population development model generated by Throne (1994) was incorporated into the aeration and storage system model. Published research data from several sources were used to quantify the effects of the grain environment on insect development. The current fecundity equation used in the model is based on data from Chesnut and Douglas (1971) for maize, Segrove (1951) for wheat, Hwang *et al.* (1983) for rice, and Birch (1953) for maize. Adults are assumed to emerge from pupae at a 1:1 gender ratio (Ungsunantwiwat and Mills, 1979). To simulate variations in developmental rates within a life stage and to move the insects from one stage to the next, a time-varying distributed delay model is used (Manetsch, 1976). As insects move through the time-varying delay model, they either stay within the current stage or move to the next one, depending on the delay value. A reinfestation model was added that uses the seven-day running average ambient temperature to determine when insects migrate into the bin (Throne, 1994). *S. zeamais* are introduced each day when the average temperature is above 20°C. If the average temperature drops below 20°C, reinfestation stops and only resumes when the ambient temperatures increase again.

Climatological data

The aeration and storage model is designed to accept hourly weather data from any geographic location. The weather data used by the model includes dry bulb temperature, relative humidity, wind speed, latitude, longitude, standard meridian, average daily horizontal radiation, and average clearness index for 1961–1990 (NCDC, 1993).

Three locations representing different maize growing regions within the United States were selected: 1) Indianapolis, Indiana; 2) Columbia, South Carolina; and 3) Amarillo, Texas. They represent the Central Maize Belt with moderate temperatures and widely fluctuating relative humidities; the Southeastern Maize Belt with warm temperatures and consistently high relative humidities; and the Southern Maize Belt with high temperatures during much of the year and low relative humidities year-round.

Management practices

The management practices simulated were: 1) no aeration; 2) no aeration with fumigation when the Federal Grain Inspection Service (FGIS) threshold of "two live weevils per kg of grain" is reached; 3) no aeration with fumigation on pre-selected dates in the fall and spring; 4) ambient fall aeration until a specific grain temperature is reached; 5) ambient fall aeration with fumigation when the FGIS threshold is reached; 6) ambient fall aeration with spring warm-up aeration; 7) fall-chilled aeration until a specific grain temperature is reached; and 8) fall-chilled aeration with summer rechilling. Fans and chillers were assumed to operate continuously from the time the bins were full until the grain was cooled to the desired grain temperatures at each respective location. Fumigation was assumed to be 100% effective, which means all insect life stages were set equal to zero. The program assumed the fumigant to be effective for 7 d before the reinfestation routine was allowed to reestablish the insect population. Practices 1 through 6 are commonly used stored-grain management practices in the United States, while practices 7 and 8 have only recently been introduced to the United States grain industry.

RESULTS AND DISCUSSION

Simulation parameters

An important step in the analysis of the various management practices was the selection of years representing good, normal, and poor storage periods. The selection was based on a statistical analysis of simulations using the 30 years of available weather data for each location (Adams, 1994). This approach saved a great deal of time running simulations and simplified the analysis. Table 1 lists the selected representative years for each location. The year selection analysis will be presented elsewhere.

Table 2 lists the input parameters valid for all three locations in the simulations of the various management strategies. The initial temperatures, moisture contents, and bulk densities

Table 1. Representative good, normal, and poor aeration and storage years for Indianapolis, Columbia, and Amarillo for weather data ranging from 1961 to 1990

Location	Good	Normal	Poor
Indianapolis	1976	1974	1965
Columbia	1967	1984	1973
Amarillo	1976	1968	1973

Table 2. Summary of input parameters valid for all three location simulations

Description	Indianapolis	Columbia	Amarillo
Starting date	10–15	09–15	08–15
Ending date	10–14	09–14	08–14
Bin height (m)	10.29	10.29	10.29
Bin diameter (m)	10.06	10.06	10.06
Air velocity (m/s)[a]	0.01247	0.01247	0.01247
Initial grain temperature (°C)	21	27	30
Initial moisture content (%w.b.)	15	14	13
Grain mass (tonnes)	598.3	595.0	591.4
Bulk density (kg/m^3)	716.6	708.4	700.1
Initial *S. zeamais* population:			
Immatures (#/25.5 kg)	0	0	0
Adult males (#/25.5 kg)[b]	1	1	1
Preoviposition female (#/25.5 kg)	0	0	0
Adult female (#/25.5 kg)[b]	1	1	1
Reinfestation rate (#/day)[c]	12	12	12

[a] 0.1 m^3 min^{-1} t^{-1} (0.1 cfm/bu).

[b] 1 adult weevil per 25.5 kg at 50–50% male–female.

[c] Number of adult pairs added per day.

were selected based on average harvest conditions for each location. The simulations used only round upright corrugated steel bins. The dimensions were selected to provide a 1:2 ratio between the total bin surface area and volume. Initial *S. zeamais* populations were selected to approximate typical levels. Earlier research indicated that a vertical grid spacing of 0.74 m, a horizontal spacing of 1.5 m, and a time-step of 3 h were sufficient for numerical accuracy (Maier, 1992).

Table 3 lists the specific inputs for the fumigation treatment simulations. Fumigations occur one month after the initial storage dates. Input parameters for the ambient aeration runs are listed in Table 4. Temperatures and spring warm-up dates were selected on the basis of common recommendations and the 30-year average ambient temperatures. Inputs for the chilled aeration simulations are summarized in Table 5. Temperature settings are for a model of a commercial German-made grain chiller previously developed and verified by Maier (1992).

Comparison of different management strategies is based on the ability to minimize the potential for spoilage and insect development. Spoilage and insect risks are defined in this research by the accumulation of dry matter loss due to the respiration of fungi and the increase in adult *S. zeamais* population, respectively. Figures 1 and 2 show the final bulk dry matter loss and *S. zeamais* populations, respectively, for good, normal and poor years and the three locations. Figures 3 – 5 show the bulk grain temperature, dry matter loss and *S. zeamais* populations during 12 months of storage in a normal year at each location.

Effect of management practice on dry matter loss (DML)

When comparing no aeration, ambient fall aeration, and fall-chilled aeration for any year in Indianapolis, the highest DML occurs in the non-aerated grain, while fall-chilled aeration predicts the least (Fig. 1). Maize stored for 12 months during a normal year using continuous ambient fall aeration and fall-chilled aeration will produce 33 and 61% less DML than not aerating the grain at all. During a normal year, maize stored at 15% m.c. without aeration

Table 3. Summary of input parameters specific for the fumigation treatments

Description	Indianapolis	Columbia	Amarillo
Periphery FGIS threshold limit (# of weevils)	118,422	118,422	118,422
Bulk FGIS threshold limit (# of weevils)	1,065,798	1,065,798	1,065,798
Fall fumigation date	11–15	10–15	09–15
Spring fumigation date	06–15	05–15	04–15

Table 4. Summary of input parameters specific for the ambient aeration treatments

Description	Indianapolis	Columbia	Amarillo
Desired grain temperature (°C)	5	12.5	7.5
Spring warm-up start date	04–15	04–29	04–22
Warm-up desired temperature (°C)	12.5	17.5	15

Table 5. Summary of input parameters specific for the chilled aeration treatments. Chiller settings are the same for all locations

Description	
Fall desired temperature (°C)	10
Fall evaporator air temperature (°C)	3
Fall reheater air temperature (°C)	9
Fall duct warming (°C)	0
Summer desired temperature (°C)	15
Summer evaporator air temp (°C)	8
Summer reheater air temp (°C)	13
Summer duct warming (°C)	1
Design airflow rate (m^3 min^{-1} t^{-1})	0.1

reaches the 0.5% limit in approximately 10 months (Fig. 3). The use of aeration limits the chance of spoilage by reducing grain temperatures to below 5°C. However, this requires three cooling cycles over 1158 h compared to 144 h for chilling (Table 6). The DML results confirm that maize stored in Indianapolis at 15% m.c. should be aerated or chilled in the fall to limit spoilage potential.

In Columbia, the desired grain temperature of 10°C can be obtained in 71% less time using chilled aeration than continuous ambient fall aeration can reach 12.5°C (Fig. 4). Once the desired

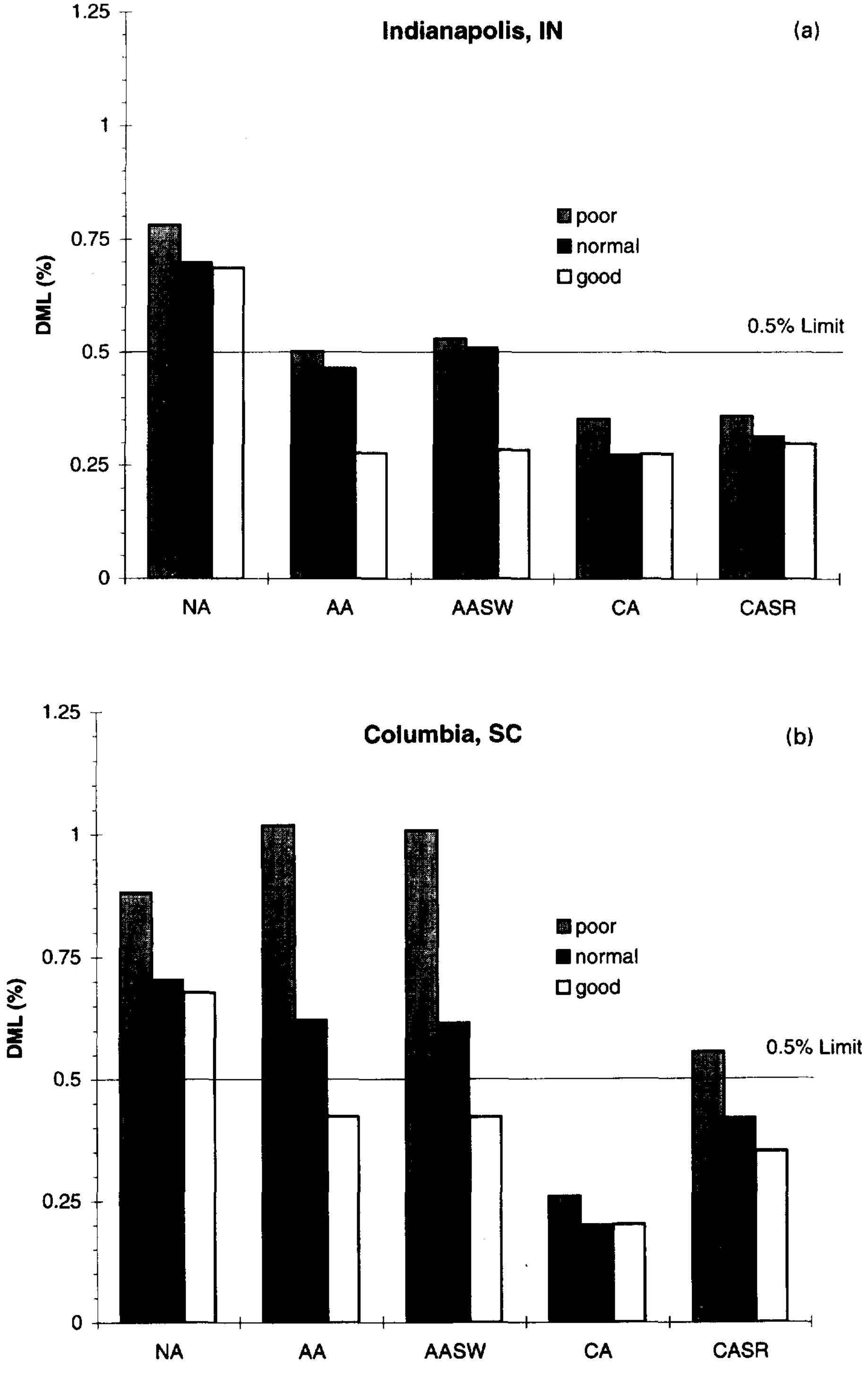

Fig. 1(a) and (b).

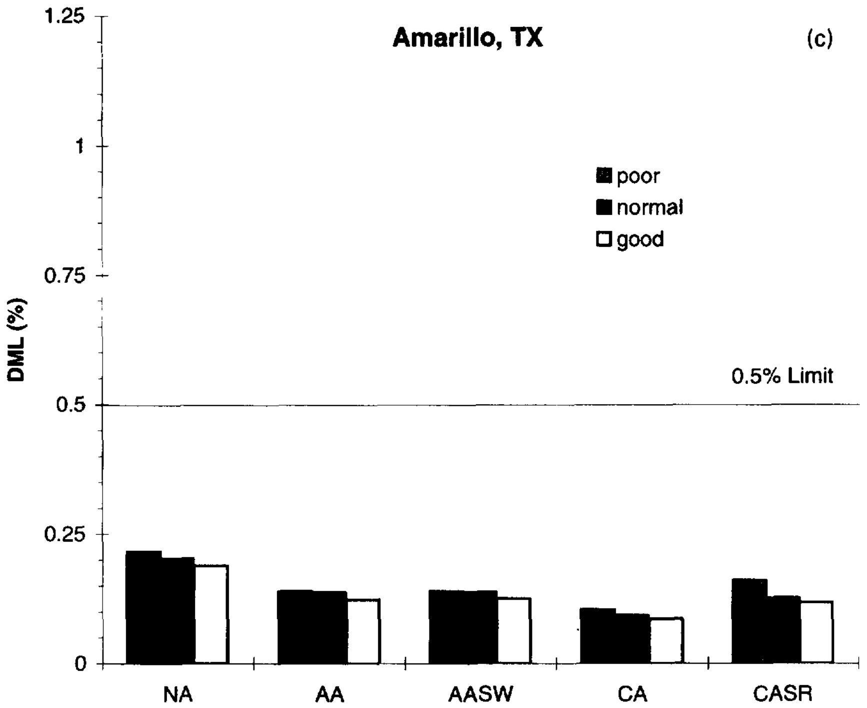

Fig. 1. Bulk dry matter loss (DML) in maize stored for 12 months in Indianapolis, Columbia, and Amarillo in good, normal, and poor years using five management practices: no aeration (NA), no ambient fall aeration (AA), ambient fall aeration and spring warm-up (AASW), fall-chilled aeration (CA), and fall-chilled aeration with summer rechilling (CASR).

grain temperatures are reached, a difference of less than 2°C exists between the two treatments for the entire storage season. The relatively high ambient temperatures in Columbia during a normal year require nearly 1500 h of continuous aeration to reach 12.5°C (Table 6). With the use of chilled aeration this time can be reduced to 417 h, while providing the advantage of eliminating five ambient temperature cycles. The DML due to aeration is above 0.5% in normal and poor years (Fig. 1). Most of the DML in the ambient fall-aerated grain occurs during aeration and not storage. The final DML in the non-aerated grain is 11% greater than for ambient fall aeration and 72% greater than for the fall-chilled aeration in a normal year. In a poor year the spoilage risk due to uncontrolled aeration is higher than not aerating in any year. Only fall-chilled aeration is able to achieve a final DML below 0.5% for any year. This indicates that maize stored in Columbia at 14% m.c. cannot be stored for 12 months in most years without a significant risk of spoilage, unless chilled aeration is utilized.

In contrast to Indianapolis and Columbia, maize stored at 13% m.c. can be safely stored in Amarillo without the risk of excessive DML for any treatment and year (Fig. 1). However, DML in the fall ambient and chilled aeration practices are 40 and 99% smaller, respectively,

Table 6. Required fan run time for each strategy investigated using a normal year (in hours)

Location	Ambient aeration	Ambient aeration with spring warm-up	Chilled aeration	Chilled aeration with summer rechilling[1]
Indianapolis	1138	1158	144	495
Columbia	1464	1471	417	3057
Amarillo	2616	2623	1617	2373

[1] Non-optimized chiller settings.

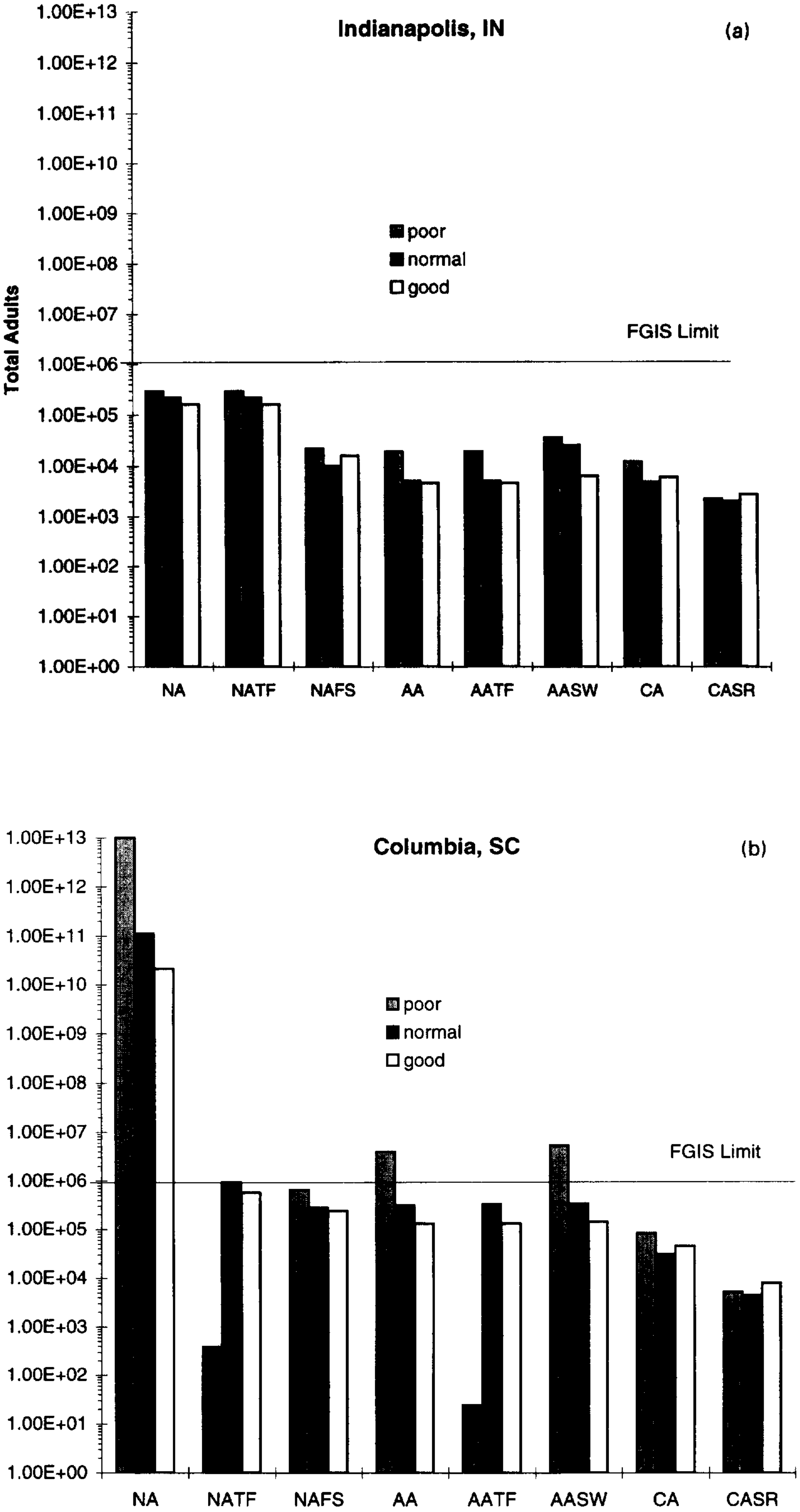
Indianapolis, IN
(a)
Total Adults
1.00E+13
1.00E+12
1.00E+11
1.00E+10
1.00E+09
1.00E+08
1.00E+07
1.00E+06
1.00E+05
1.00E+04
1.00E+03
1.00E+02
1.00E+01
1.00E+00
poor
normal
good
FGIS Limit
NA
NATF
NAFS
AA
AATF
AASW
CA
CASR
Columbia, SC
(b)
Total Adults
1.00E+13
1.00E+12
1.00E+11
1.00E+10
1.00E+09
1.00E+08
1.00E+07
1.00E+06
1.00E+05
1.00E+04
1.00E+03
1.00E+02
1.00E+01
1.00E+00
poor
normal
good
FGIS Limit
NA
NATF
NAFS
AA
AATF
AASW
CA
CASR

Fig. 2(a) and (b).

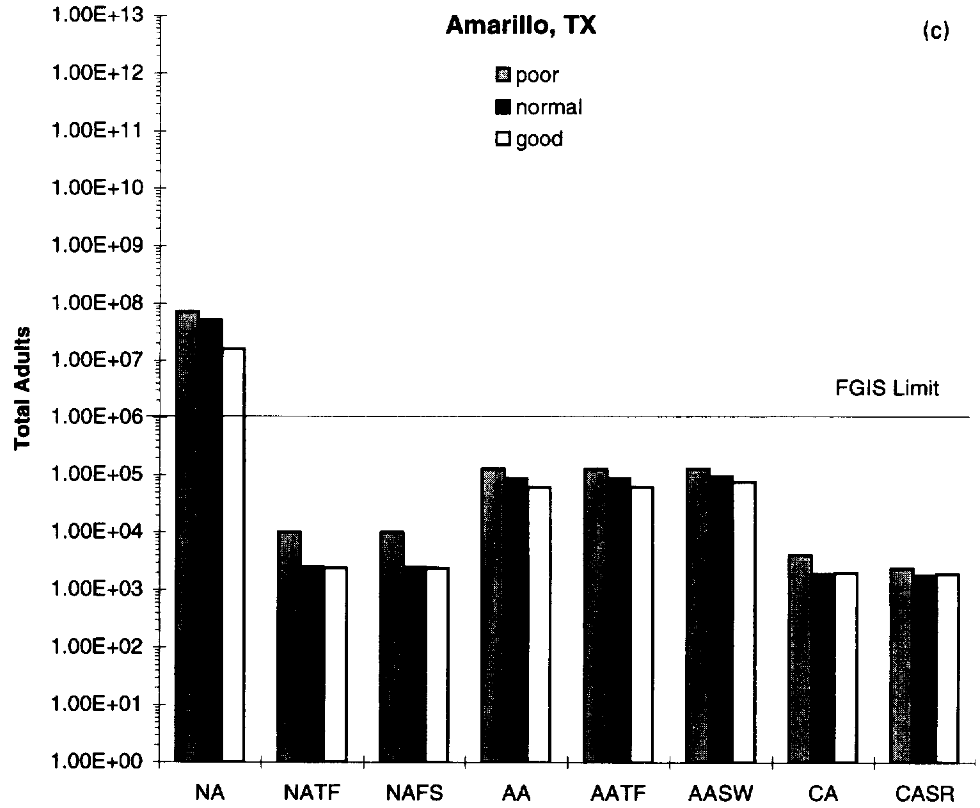

Fig. 2. Bulk total adult *S. zeamais* populations in maize stored for 12 months in Indianapolis, Columbia, and Amarillo in good, normal, and poor years using eight management practices: no aeration (NA), no aeration and FGIS threshold fumigation (NATF), no aeration and calendar-based fall and spring fumigation (NAFS), ambient fall aeration (AA), ambient fall and FGIS threshold fumigation (AATF), ambient fall aeration and spring warm-up (AASW), fall-chilled aeration (CA), and fall-chilled aeration with summer rechilling (CASR).

than in the non-aerated grain. The use of continuous ambient fall aeration requires ten cycles of over 2600 h to reach the desired temperature of 7.5°C while fall-chilled aeration requires over 1600 h to reach the target temperature for chilling of 10°C, as the simulated chiller settings were not optimized for 13% grain m.c. Optimization depends on the proper combination of chiller settings that match the appropriate equilibrium moisture content (EMC). On average, Amarillo experiences less than half the DML observed in Indianapolis and Columbia, despite having higher grain temperatures throughout the storage period. This illustrates the importance of m.c. in determining the risk of grain spoilage. DML in Columbia is generally higher than in Indianapolis primarily because the bulk of the grain is as much as 7°C warmer than in Indianapolis.

The use of continuous ambient fall aeration is predicted to cause the highest initial DML rate early in the storage season compared to chilled aeration and no aeration for any location and year. The high and low cycling of the grain temperature is considered to be the primary cause. The lack of temperature control is the main disadvantage of continuous ambient fall aeration. Chilled aeration avoids moving multiple temperature fronts through the grain by controlling the inlet temperature and relative humidity, making possible a predictable and much shorter time period to cool grain. With the use of an automatic aeration controller, the efficiency of the ambient aeration strategy could probably be improved significantly. Unfortunately, few controllers are used by commercial elevator managers and farmers in the United States. Indeed, most turn on aeration fans at the time of filling a bin and operate them continuously until ‘safe’ grain- storage temperatures are reached in the late fall.

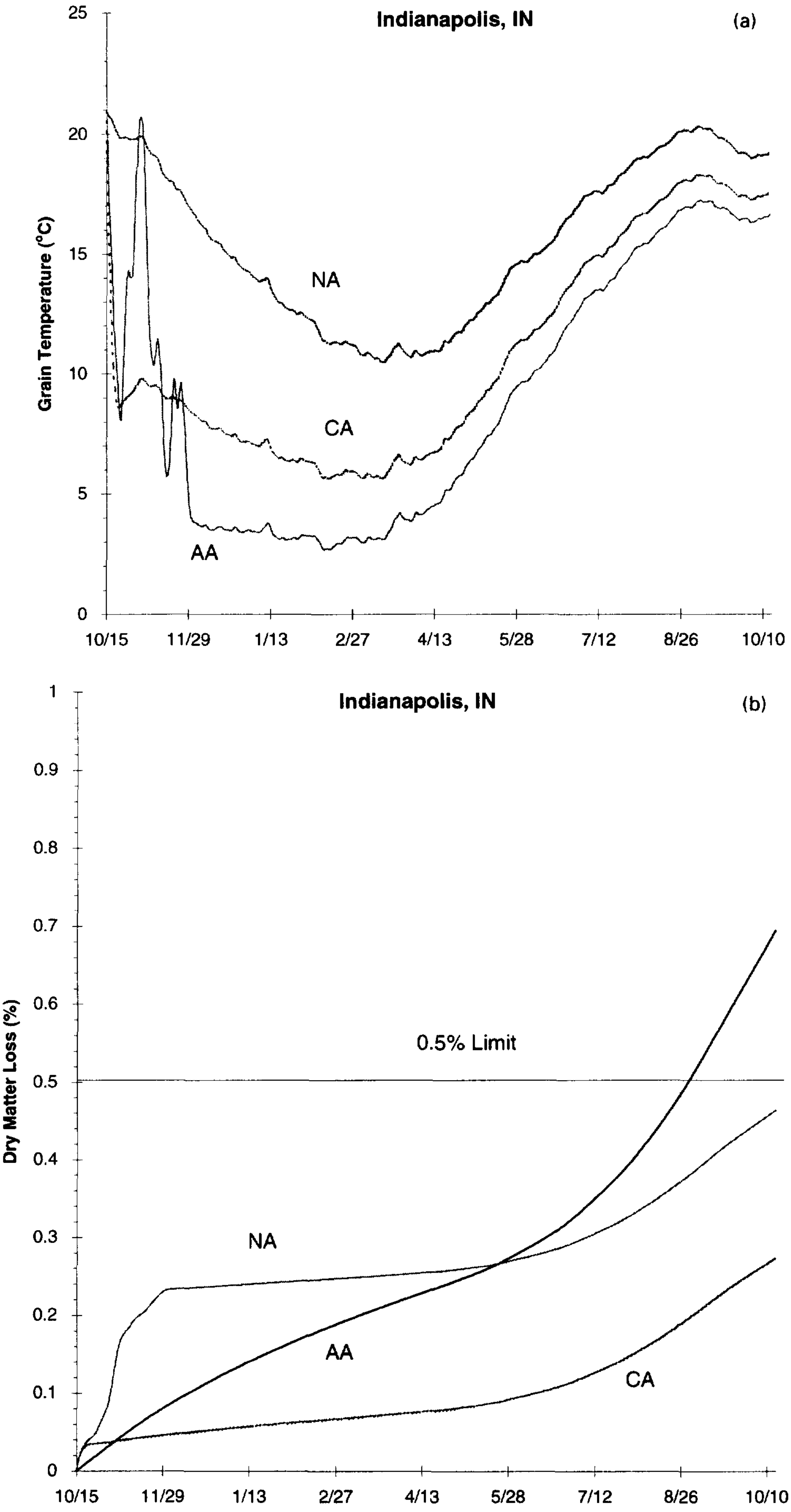
Indianapolis, IN
(a)
Grain Temperature (°C)
25
20
15
10
5
0
NA
CA
AA
10/15
11/29
1/13
2/27
4/13
5/28
7/12
8/26
10/10
Indianapolis, IN
(b)
Dry Matter Loss (%)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.5% Limit
NA
AA
CA
10/15
11/29
1/13
2/27
4/13
5/28
7/12
8/26
10/10

Fig. 3(a) and (b).

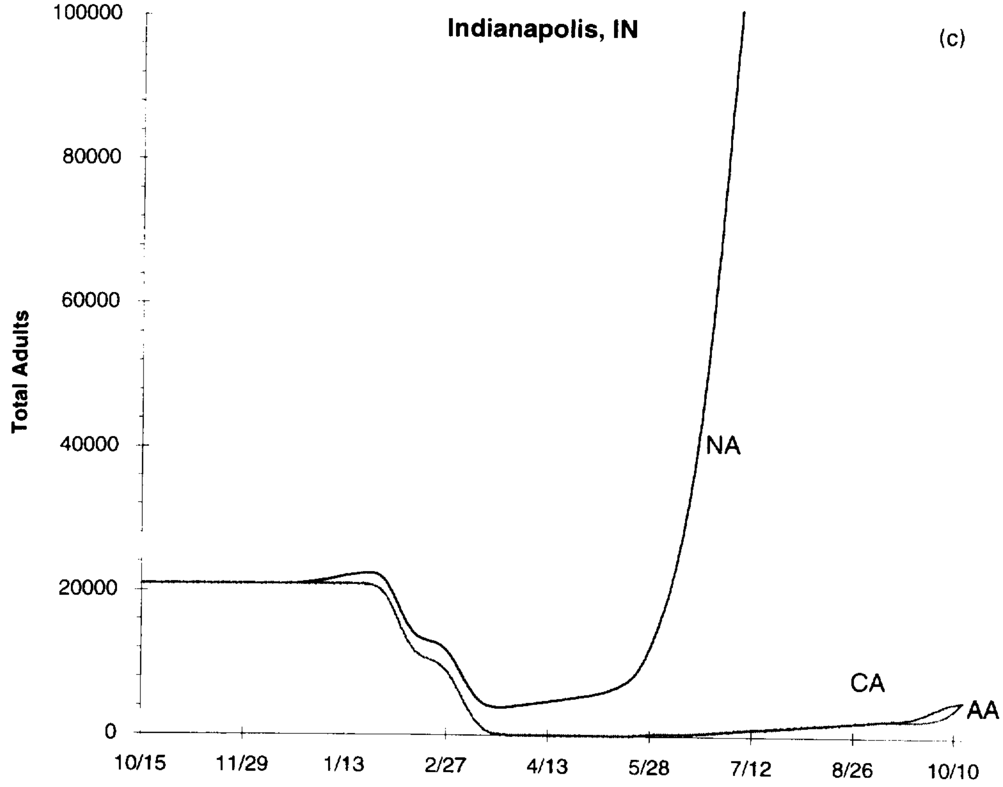

Fig. 3. Bulk temperature, dry matter loss, and *S. zeamais* populations for Indianapolis, using no aeration (NA), ambient fall aeration (AA), and fall-chilled aeration (CA) in a normal year.

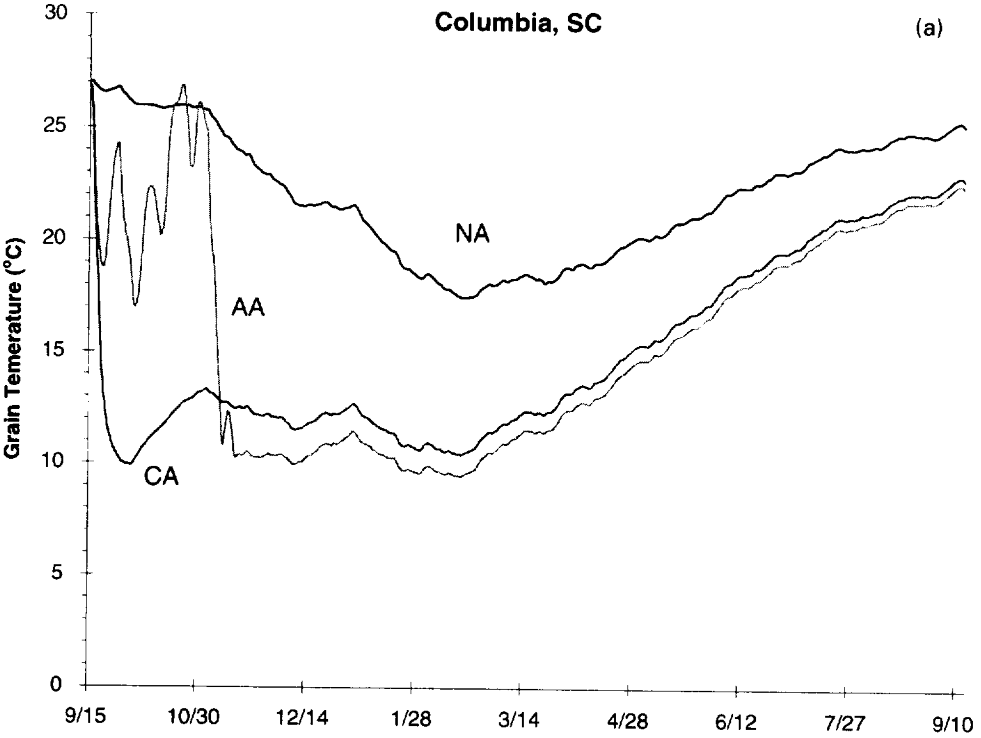

Fig. 4(a). (Legend on p. 266.)

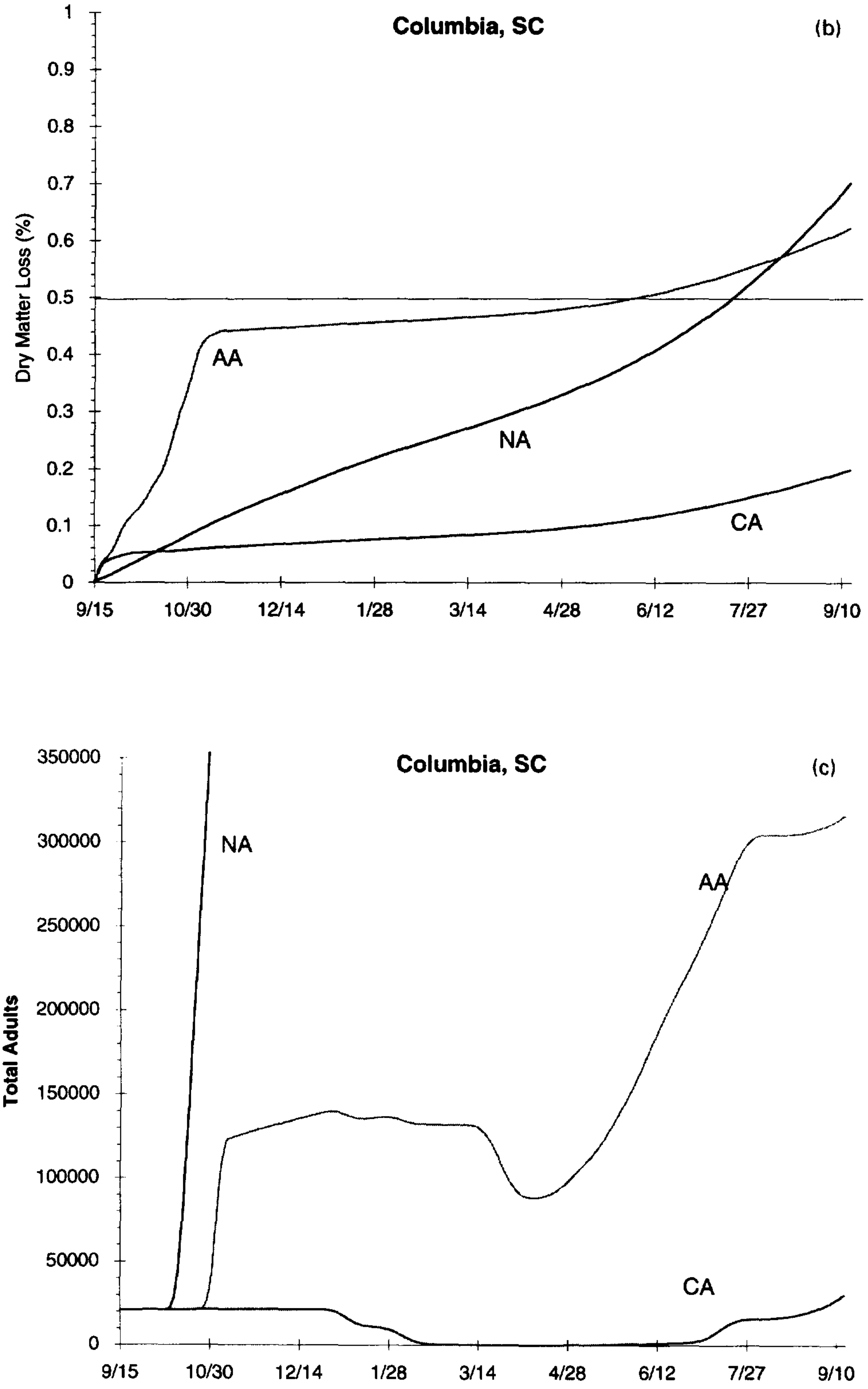

Fig. 4. Bulk temperature, dry matter loss, and *S. zeamais* populations for Columbia, using no aeration E(NA), ambient fall aeration (AA), and fall-chilled aeration (CA) in a normal year.

Spring warming of grain is frequently recommended to reduce temperature gradients between different areas within a bin and the ambient conditions (McKenzie *et al*., 1980). The use of spring aeration in Indianapolis to warm grain to within 10°C of the average maximum summer temperature results in about a 10% higher bulk DML during any year than using ambient fall aeration only (Fig. 1). Spring warm-up in Columbia and Amarillo requires only a few hours, because grain temperatures already warmed significantly before the selected aeration date. No change in final DML was observed in either location. Thus, no benefit is to be gained by warming grain in the spring with respect to minimizing DML.

The use of summer rechilling in any year at any location increases bulk DML compared to fall-chilled aeration only. However, in comparison to ambient aeration in normal and poor years, the final bulk DML after 12 months of storage remains below the 0.5% limit in any year. The reason for this phenomenon lies in the fact that the rechilling front has to move a warming front through the still cool grain bulk because grain near the plenum of the bin had warmed. Warming of cool grain followed by recooling increases the DML rate, and results in higher final DML values. Thus, multiple recooling of a grain bulk whether with ambient or chilled air should be avoided.

Effect of management practice on S. zeamais *population*

The use of aeration is predicted to significantly reduce the development of *S. zeamais* in maize stored for more than six months in Indianapolis (Fig. 3). Ambient fall aeration is predicted to be as effective at controlling *S. zeamais* populations as fall-chilled aeration. At the end of 12 months of storage in a normal year, both aeration strategies predict final bulk populations of less than one weevil per 102 kg, which is well below the FGIS threshold of 2 insects per kg. If considering only insect development, fall-chilled aeration has no significant advantage over ambient fall aeration because it only shows a 4% improvement in final *S. zeamais* population control (Fig. 2). Therefore, low fall and winter ambient temperatures can provide adequate insect control for maize stored through the following summer in Indianapolis for all years.

Without aeration, the *S. zeamais* population develops extremely quickly in Columbia (Fig. 4). The FGIS threshold is reached in less than two months in the grain bulk. Thus, maize clearly cannot be stored in Columbia without some type of insect control. The *S. zeamais* population in the fall-aerated maize increases similarly to the non-aerated grain. However, once the grain temperature reaches the desired 12.5°C, the rate of increase is essentially stopped. The population starts to increase again in the spring until the final population is ten times larger than for the fall-chilled aeration treatment. Both chilled and ambient aeration (except in a poor year) maintain bulk insect populations below the FGIS threshold for the entire storage period (Fig. 2). A resulting 90% improvement observed in the final insect population indicates that fall-chilled aeration can be significantly effective at controlling populations in sub-tropical climates in any year (Fig. 4).

The relatively high temperatures in the non-aerated grain provide an ideal environment for insects to develop in Amarillo (Fig. 5). Without aeration the grain reaches the FGIS threshold in November, less than three months after the initial storage date. The use of ambient and chilled fall aeration maintains the populations significantly below the threshold (Fig. 2). The population in the chilled grain is nearly non-existent, while the ambient fall-aerated population after 12 months is approximately one weevil per 6 kg in a normal year. This is a 97% improvement in *S. zeamais* control.

Warming grain in the spring of a normal year in Indianapolis increases the bulk *S. zeamais* population by 390% compared to fall ambient aeration. As in Indianapolis, increasing the grain temperature in Columbia accelerates insect development. The final populations are increased by at least 6% in any year relative to fall ambient aeration. The usefulness of spring warm-up in Amarillo is limited also because the grain temperature has already started to increase before the selected aeration date. Insect populations increase by at least 7% compared to ambient fall aeration only. The use of ambient fall aeration with spring warm-up proves only to increase insect problems relative to ambient fall aeration only in all locations and representative years.

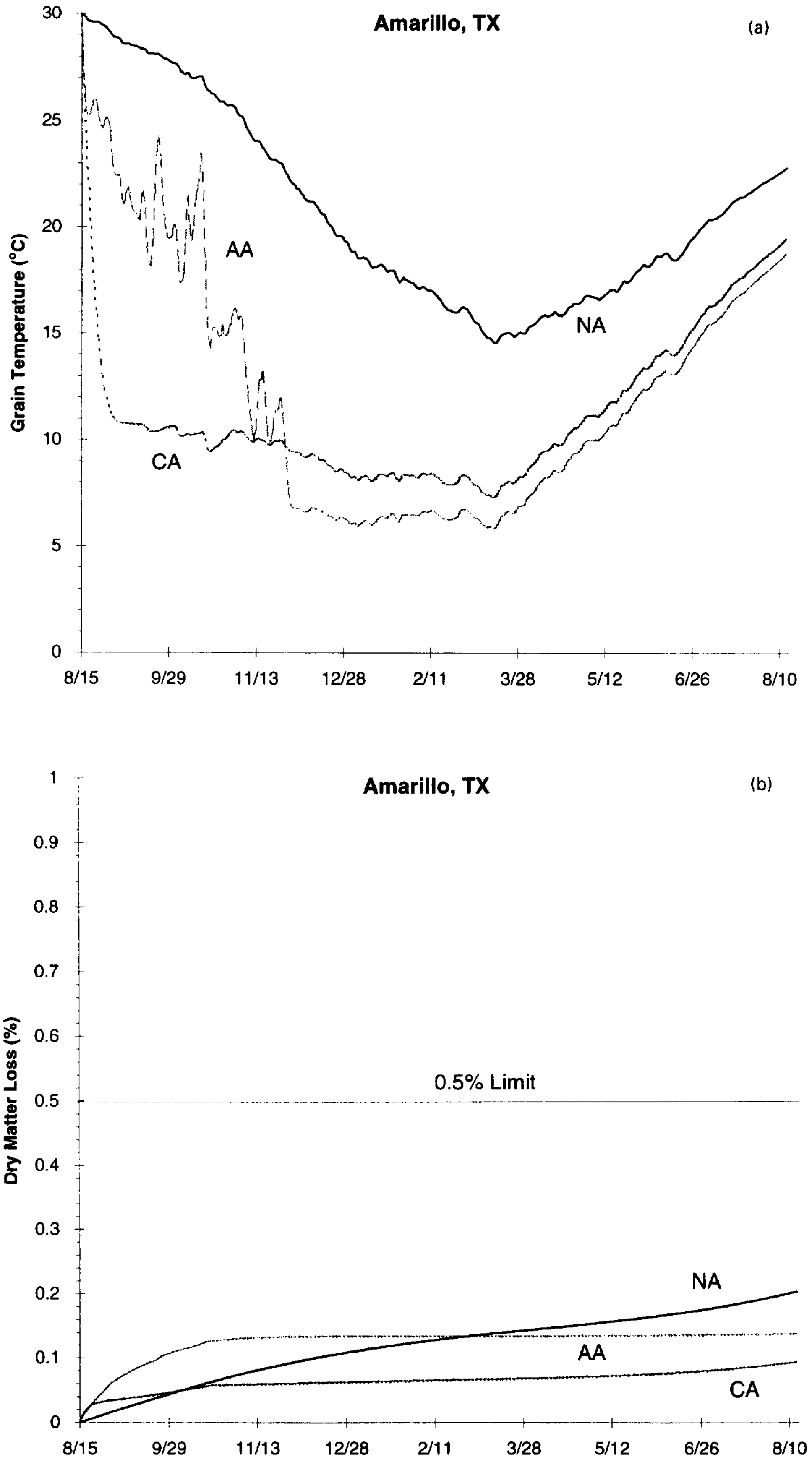
Amarillo, TX
(a)
Grain Temperature (°C)
30
25
20
15
10
5
0
AA
NA
CA
8/15
9/29
11/13
12/28
2/11
3/28
5/12
6/26
8/10
Amarillo, TX
(b)
Dry Matter Loss (%)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.5% Limit
NA
AA
CA
8/15
9/29
11/13
12/28
2/11
3/28
5/12
6/26
8/10

Fig. 5(a) and (b).

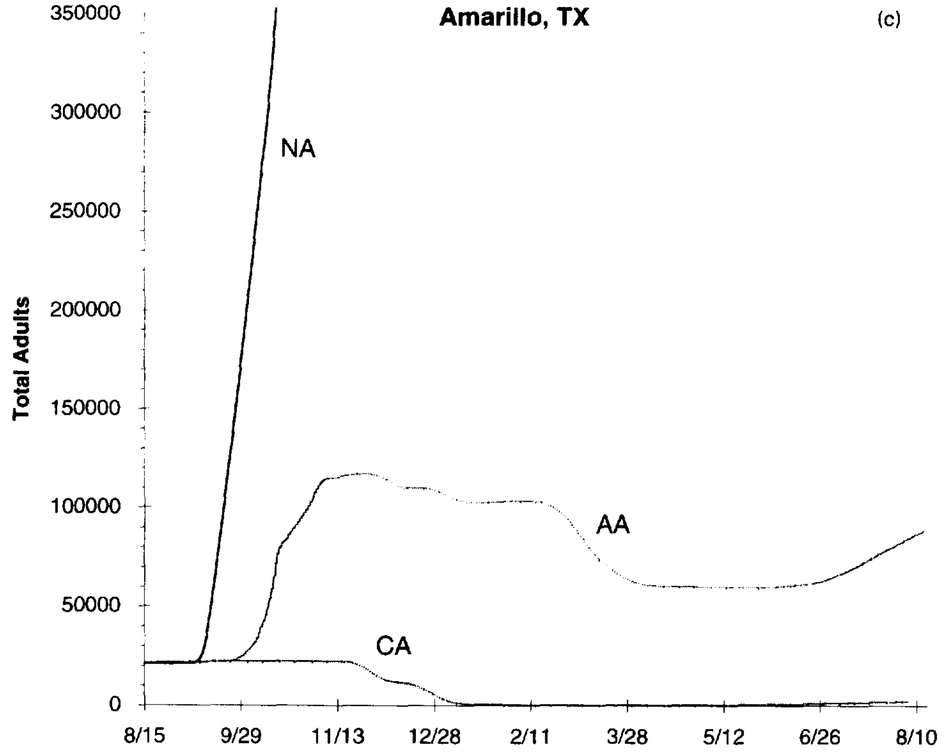

Fig. 5. Bulk temperature, dry matter loss, and *S. zeamais* populations for Amarillo, using no aeration (NA), ambient fall aeration (AA), and fall-chilled aeration (CA) in a normal year.

Warming of grain to within 10°C of the average maximum summer ambient temperature should only be done when considered absolutely necessary. When deciding to use spring aeration, consideration of possible insect problems must be weighed carefully against the benefits of uniform grain temperatures. Instead, grain should be cooled in the fall and winter, and the fans covered to reduce the warming rate in the spring.

The use of summer rechilling to maintain grain temperatures below 17°C has a beneficial effect on insect populations. Bulk *S. zeamais* populations are reduced by 59% in a normal year in Indianapolis compared to fall-chilled aeration only. In Columbia, supplementing the use of fall-chilled aeration with summer rechilling reduces the *S. zeamais* populations by 85%, when compared to fall chilling only. The system model predicts that the FGIS threshold will not be reached anywhere in the bin with the use of summer rechilling. The benefits of summer rechilling are even greater when compared to ambient fall aeration only. The biggest difference between Columbia and Indianapolis is the amount of time required to obtain the better control. In Columbia a non-optimized chiller would have to operate essentially continuously, while Indianapolis only requires 21 d. Once again, this indicates the need to optimize the chiller operation. The use of fall-chilled aeration and summer rechilling decreased the final *S. zeamais* population by 5% in the normal and good years in Amarillo compared to fall-chilled aeration only. However, populations decreased by nearly 41% during a poor storage year. Summer rechilling is effective in keeping the grain temperature below 17°C, and ensuring slow insect development. The substantial decrease in insect populations must be weighed against the expense of the additional aeration time of an optimized chiller versus potential fumigation costs.

Table 7 lists the number of times fumigation is required for the different strategies and locations. When no aeration is used, fumigation becomes most critical, especially in Columbia,

Table 7. Required number of fumigation treatments for the three maize storage locations during a normal year

Location	No aeration with threshold fumigation		Ambient aeration with threshold fumigation		Fall/Spring fumigations
	Bulk	Periphery	Bulk	Periphery	Bulk/ Periphery
Indianapolis	0	1	0	1	2
Columbia	1	2	0	1	2
Amarillo	1	1	0	0	2

Table 8. Final grain moisture content (% w.b.) using four aeration practices in a normal year

Location	Ambient aeration	Ambient aeration with spring warm-up	Chilled aeration	Chilled aeration with summer rechilling[1]
Indianapolis	14.37	14.45	14.57	14.51
Columbia	12.83	12.85	13.40	13.59
Amarillo	10.51	10.54	12.59	12.77

which reaches the FGIS threshold a second time in the periphery. The addition of ambient fall aeration makes the fumigation of maize stored in Amarillo unnecessary, while requiring that maize stored in Indianapolis and Columbia be fumigated once in late summer shortly before removing the grain from storage. It is interesting to note that with threshold fumigation final bulk population levels are significantly higher in Amarillo in fall-aerated maize compared to non-aerated maize. Also, the use of fall and spring fumigations in a normal year predict final bulk populations to be 97% smaller than for ambient fall aeration, but 31% larger than with chilled aeration (Fig. 2).

In each location, the use of calendar-based fall and spring fumigation is undesirable. Fumigating only when the level of insects is high enough to cause a loss in grain value is a more effective pest management practice. It corresponds to the philosophy of integrated pest management, which bases therapeutic action on the economic threshold principle.

Effect of management practice on shrink loss

Water shrink is a major economic factor when stored grain managers consider chemical (fumigation) versus physical (aeration) pest management costs. Table 8 summarizes the final grain moisture contents for a normal year in each of the locations using the four aeration practices. The system model assumes that changes in moisture content only occur during aeration. With ambient aeration, the final m.c. reflect the r.h. levels in each location. Indianapolis and Columbia are relatively humid regions compared to Amarillo and experience shrink losses of 0.74 and 1.34%, respectively. The decrease in Amarillo is 2.78%. This implies that almost 3% of the original mass of grain initially placed into storage could be lost due to uncontrolled ambient aeration. At a market price of $118 per tonne of maize, a 3% shrink loss is worth $3.54 per tonne. When spring warm-up aeration is used in addition to ambient fall aeration, slight rewetting occurs in each of the locations due to higher relative humidities. The use of fall-chilled aeration minimizes the amount of moisture loss by controlling the EMC of the inlet air. Shrink losses are then 0.50, 0.69 and 0.47% for Indianapolis, Columbia and Amarillo, respectively. This represents an average shrink cost of $0.65 per tonne for fall chilling at any of the three locations. Like spring warm-up, the use of summer rechilling increases the moisture contents for Columbia and Amarillo confirming the non-optimized operation of the chiller.

Management practice recommendations for each location

Controlling DML and *S. zeamais* population in any location and any year can best be achieved using fall-chilled aeration with summer rechilling. Chilled aeration is predictable and the most effective strategy, although the chilling process has to be optimized for each location. DML is kept below 0.5%, and insect populations are prevented from reaching the FGIS threshold without the need for fumigation. Additionally, shrink loss is least in maize cooled with chilled air in any location and year. No aeration is by far the most undesirable management practice due to the high grain quality loss for any location and year. Residual pesticides and fumigation of properly cooled maize storages should not be necessary in the United States.

Indianapolis experiences low enough winter temperatures to allow safe storage of fall harvested maize into the following summer using ambient fall aeration in most years. Ambient fall aeration is as effective at controlling bulk *S. zeamais* populations as fall-chilled aeration, but may cause high DML rates if the fan operation is not controlled. For safe storage, grain temperatures should be lowered to below 10°C by late October and below 5°C by late November.

Due to the sub-tropical temperatures, chilled aeration is the only aeration strategy suited for use in Columbia for any length of storage during any year. Ambient fall aeration can control insect population for storage periods of up to 8 months during normal and good years. However, with continuous ambient fall aeration, DML becomes unacceptably high. This might be overcome by using an aeration controller to operate the fans only when the temperature and r.h. conditions are favorable. The fan should be operated selectively to lower grain temperatures below 20°C by early October, and below 12.5°C by mid-November. However, ambient aeration requires the use of threshold-based fumigation to keep increasing insect populations under control. Repeat treatments may be necessary.

Maize stored at 13% moisture content can be stored for 12 months without aeration and fear of spoilage in Amarillo. However, *S. zeamais* populations are extremely high without temperature control. Ambient fall aeration is adequate to maintain populations below the FGIS threshold for the entire period for most years. However, continuous ambient fall aeration requires a substantial amount of aeration time causing costly shrink losses, which are avoided with chilled aeration. A controlled aeration strategy could substantially reduce aeration time from 2600 h to less than half. Grain temperatures can be reduced with ambient air below 20°C by mid-September, below 15°C by mid-October, and below 10°C by mid-November.

REFERENCES

Adams W. H. (1994) Development of a prototype post-harvest aeration and storage trainer. M.S. Thesis, Purdue University, West Lafayette, IN.

Adams W. H., Mason L. J., Maier D. E. and Obermeyer J. L. (1993) Comparison of stored-insect management techniques—A progress report. Paper No. 93-6513. ASAE, St Joseph, MI.

Alagusundaram K., Jayas D. S., White N. D. G. and Muir W. E. (1990) Three-dimensional, finite element, heat transfer model of temperature distribution in grain storage bins. *ASAE Transactions* **33,** 577–584.

Bailey J. E. (1992) Whole grain storage. In *Storage of Cereal Grains and Their Products* (Edited by Sauer D.B.), pp. 157–187. AACC, St Paul, MN.

Birch L. C. (1953) Experimental background to the study of the distribution and abundance of insects—I. The influence of temperature, moisture and food on the innate capacity for increase of three grain beetles. *Ecology* **34,** 698–711.

Brook R. C. (1987) Modelling grain spoilage during near-ambient grain drying. Divisional Note 1388. AFRC Institute of Engineering Research, Silsoe, U.K.

Burrell N. J. (1982) Refrigeration. In *Storage of Cereal Grains and Their Products* (Edited by Christensen C. M.), pp. 407–441. AACC, St Paul, MN.

Burges H. D. and Burrell N. J. (1964) Cooling bulk grain in the British climate to control storage insects and to improve keeping quality. *Journal of Scientific Food and Agriculture* **15,** 32–50.

Chesnut T. L. and Douglas W. A. (1971) Competitive displacement between natural populations of the maize weevil and the Angoumois grain moth in Mississippi. *Journal of Economic Entomology* **64,** 864–868.

Flinn P. W. and Hagstrum D. W. (1990) Stored Grain Advisor: A knowledge-based system for management of insect pests of stored grain. *Artificial Intelligence Applications in Natural Resource Management* **4,** 444–452.

Hwang J. S., Hsieh F. K. and Kung K. S. (1983) Influences of temperature and relative humidity on the development and reproduction of the maize weevil *Sitophilus zeamais* Motschulsky. *Plant Protection Bulletin* (*Taiwan*) **24,** 41–52.

Kawamoto H., Sinha R. N. and Muir W. E. (1992) Computer simulation modeling for stored-grain pest management. *Journal of Stored Products Research* **28,** 139–145.

Maier D. E. (1992) The chilled aeration and storage of cereal grains. Ph.D. dissertation, Michigan State University, East Lansing, MI.

Maier D. E., Rulon R. A., Guiffre A. F. and Wilson C. (1993) Development of a new commercial grain chiller. Paper No. 93-6514. ASAE, St Joseph, MI.

Maier D. E. (1994) Chilled aeration and storage of U.S. crops — A review. In *Stored Product Protection* (Edited by Highley E., Wright E. J., Banks J. H. and Champ B. R.), pp. 300–311. University Press, Cambridge, U.K.

Manetsch T. J. (1976) Time-varying distributed delays and their use in aggregative models of large systems. *IEEE Transactions on Systems, Man, and Cybernetics* **6,** 547–553.

McKenzie B. A., Van Fossen L., Foster D. E. and Stockdale H. J. (1980) Managing dry grain in storage. AED-20. MWPS, Iowa State University, Ames, IA.

NCDC (1993) Solar and Meteorological Surface Observation Network, 1961–1990, Version 1.0. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, NCDC, Ashville, NC.

Noyes R. T., Weinzierl R., Cuperus G. W. and Maier D. E. (1995) Stored grain management techniques. In *Stored Product Management* (Edited by Krischik V., Cuperus G. W. and Galliart D.), pp. 71–84. Cooperative Extension Service, Oklahoma State University, Stillwater, OK.

Parry J. L. (1985) Mathematical modelling and computer simulation of head and mass transfer in agricultural grain drying: a review. *Journal of Agricultural Engineering Research* **32,** 1–29.

Pedersen J. R. (1992) Insect: identification, damage, and detection. In *Storage of Cereal Grains and Their Products* (Edited by Sauer D. B.), pp. 435–489. AACC. St Paul, MN.

Segrove F. (1951) Oviposition behaviour in the two strains of the rice weevil, *Calandra oryzae* Linn. (Coleopt. Curculionidae). *Journal of Experimental Biology* **28,** 281–297.

Steele J. L., Saul R. A. and Hukill W. V. (1969) Deterioration of shelled corn as measured by carbon dioxide production. *ASAE Transactions* **12,** 685–689.

Strohine R. L. and Yang X. (1990) Effects of hybrid and grain damage on estimated dry matter loss for high-moisture shelled corn. *ASAE Transactions* **33,** 1291–1298.

Thompson T. L. (1972) Temporary storage of high-moisture shelled corn using continuous aeration. *ASAE Transactions* **15,** 333–337.

Throne J. E. (1994) Life history of immature maize weevils (Coleoptera: Curculionidae) on corn stored at constant temperatures and relative humidities in the laboratory. *Environmental Entomology* **23**, 1459–1471.

Ungsunantwiwat A. and Mills R. B. (1979) Influence of medium and physical disturbances during rearing on development and numbers of *Sitophilus* progeny. *Journal of Stored Products Research* **15**, 37–42.