Feasibility of Aeration for Management of Maize Weevil Populations in Corn Stored in the Southern United States: Model Simulations Based on Recorded Weather Data

Frank H. Arthur, James E. Throne, Dirk E. Maier, and Michael D. Montross

ABSTRACT Recorded data from weather stations in 11 southern states were used to determine the optimum initial activation temperatures for immediate cooling of corn that is stored after harvest. Hours of temperature accumulation in September and October that were below 12.8 and 15.6°C (55 and 60 °F), levels that often are recommended for fall cooling of hard red winter wheat stored in the midwestern United States, were calculated and plotted, along with hours of accumulation below 18.3°C (65°F). Five geographic zones were delineated based on weather data from 53 stations; and a bin-cooling model, which was integrated with a model for maize weevil development, was used to predict weevil population growth in unaerated corn and corn aerated at 12.3, 15.6, and 18.3°C with airflow rates of 0.0013, 0.0026, and 0.0039 $m^3/s/m^3$ (0.1, 0.2, 0.3 cubic feet per minute per bushel). The time required to compete a cooling cycle within each region was estimated for each of the 9 temperature-airflow rate combinations. Aeration at 15.6 or 18.3°C, depending on the geographic zone, and an airflow rate of 0.0013 $m^3/s/m^3$ resulted in the lowest number of maize weevils. In all zones, aeration dramatically reduced the predicted number of maize weevils compared to population levels in unaerated corn.

CORN (*Zea mays* L.) IS AN IMPORTANT STORED COMMODITY IN MUCH of the eastern United States and can be infested and damaged by a variety of internally and externally-feeding insect species (Arbogast and Throne 1997). One of the primary internal feeders is the maize weevil, *Sitophilus zeamais* Motschulsky (Fig. 1). The female oviposits in the kernel, and the resulting larva feeds, develops, and pupates within the kernel; the callow adult then chews its way out. This insect rarely is present in field corn but can quickly locate and infest stored corn. The lower developmental threshold for most stored-product pests is approximately 18°C (Howe 1965), but the threshold for maize weevil development is somewhere between 10 and 15°C (Throne 1994). The life cycle is completed in ≈6 weeks under laboratory rearing conditions of 27°C, 60% RH.

In the United States, corn can be harvested from mid-August in southern Texas to early November along the Canadian border. In the northern latitudes, ambient temperatures at the time of harvest are near the lower developmental threshold for maize weevils, which would limit population development should infestations occur after the corn is binned. Populations would be further limited as temperatures continue to decrease as the fall season progresses. However, temperature conditions in the southern United States are more favorable for maize weevil population growth and development. According to the crop production statistics for most of the states in the southern United States, corn harvest begins in late August to mid-September. Average daily temperatures are well above 15–18°C and, depending on binning date and latitude, ambient temperatures may not be cool enough to limit weevil populations for months. Corn can be treated with a protectant insecticide when it is binned, but, now that malathion is not being supported for re-registration on stored corn, the only conventional insecticide labeled as a corn protectant is the organophosphate insecticide pirimiphos-methyl. However, there are several biological and sociological considerations for reducing the use of insecticidal protectants—the development of insecticide resistance, consumer preferences for residue-free

Fig. 1. Adult maize weevil *Sitophilus zeamais* on corn.

products, and a growing emphasis on using alternatives to chemicals whenever possible (Arthur 1996).

Cooling stored small grains through low-volume aeration to limit insect pest development is an important component of management plans in the midwestern (Cuperus et al. 1986, 1990) and north central states (Gardner et al. 1988). Initial aeration activation temperatures (the temperature at which cooling is initiated) of 12–15°C are recommended for stored wheat (Storey et al.1979, Noyes et al. 1987, Cuperus et al. 1990), but these temperatures normally will not occur until fall. Wheat is harvested during the summer when temperatures are often ≥30°C and these high temperatures may inhibit initial population growth if infestations occur shortly after the wheat is binned (Noyes et al. 1987). The optimum developmental range of many stored-grain insect pests is ≈25–33°C (Fields 1992). Once temperatures begin to cool in the fall, an initial activation temperature of 15°C would rapidly cool wheat through the range that is favorable for insects to levels where population development would be limited (Noyes et al. 1987).

Theoretical calculations show that a cycle of 120 h of temperatures below a specified temperature (the activation temperature) are required to cool the entire grain mass to this temperature at an airflow rate of 0.0013 $m^3/s/m^3$, or 0.1 cubic ft per min per bushel (McCune et al. 1963). These theoretical equations also indicate that increasing the airflow rates to 0.0026 and 0.0039 $m^3/s/m^3$ (0.2 and 0.3 cubic ft per min per bushel) reduces the time required to complete a cycle of 60 and 40 h, respectively. Noyes et al. (1987) recommended an activation temperature of 12.8°C (55°F) for fall cooling of wheat stored in Oklahoma. Automatic aeration fan controllers that can be set to operate only when temperatures fall below the set point also are recommended.

Comparatively little work has been done with aeration on stored corn, possibly because temperatures are already cool enough to limit insect populations at the time corn is harvested and binned in the northern United States. There are a few engineering guidelines for the use of aeration on corn in the southern United States, but these recommendations often are based on winter cooling, with little emphasis on initial activation temperatures. Recent research studies have shown that aeration can be used to limit pest populations in corn stored in Georgia (Arthur 1994, Arthur and Throne 1994). Another study showed that an initial cooling cycle of 12.8°C could not be completed until late October at an airflow rate of 0.0013 $m^3/s/m^3$. However, increasing the activation temperature from 12.8 to 15.6°C and from 15.6 to 18.3°C advanced the calendar date for completing a cooling cycle by approximately 7–10 d for each temperature increment (Arthur and Johnson 1995), which could limit the development of insect pest populations.

The objectives of this study were to: (1) estimate hours of temperature accumulations below activation temperatures of 12.8, 15.6, and 18.3°C in the southern United States during the months of September and October; (2) use data from selected weather stations to subdivide the southern region into different zones representing geographic variation in corn harvesting and binning dates; (3) estimate dates within each zone by which aeration cooling cycles of 120, 60, and 40 h (which correspond to airflow rates of 0.0013, 0.0026, and 0.0039 $m^3/s/m^3$, respectively) could be completed at each activation temperature; and (4) estimate the impact of aeration at these different temperature-airflow rate combinations on the development of maize weevil populations in each zone.

Materials and Methods

The states chosen to represent corn storage in the southern region were Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, North Carolina, Oklahoma, South Carolina, Tennessee, and Texas. According to crop production statistics for these states, the bulk of the corn harvest occurs sometime during September. The date of corn harvest is assumed to be roughly dependent on latitude, and this date would normally occur earlier in the deep south than along the northern borders of Arkansas, North Carolina, Oklahoma, and Tennessee, which are on the same approximate latitudinal plane.

Recorded daily high and low temperatures for various weather stations in each state were obtained from a CD-ROM from Earth Info (Boulder, CO). Stations within a state were selected based on 95% coverage of data points between the years 1960 and 1989. This filtering process yielded a range of stations from 36 for Louisiana to 150 for Texas. Daily sunrise and sunset at each station were estimated using a model that calculates daily sunrise and daily sunset based on latitude, longitude, and time zone. The 30-year temperature data were averaged using the Means Procedure of the Statistical Analysis System (SAS Institute 1987). A model that calculates hourly temperature based on the daily high and low temperatures, sunrise, and sunset was used to estimate total hours of temperature accumulation below 12.8, 15.6, and 18.3°C in September and October at each selected weather station (Arthur and Johnson 1995). Contour lines for each temperature accumulation during September and October for the southern region were estimated using Surfer software (Golden CO). These contour lines were then incorporated into maps using MapInfo software (Ithaca NY) (Figs. 2 and 3).

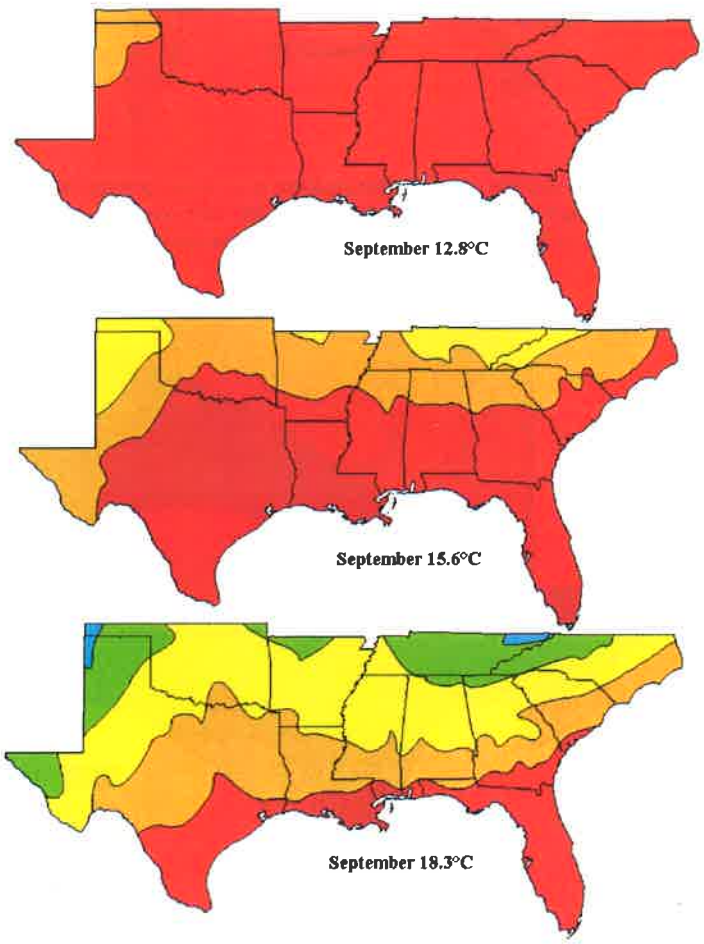

Fig. 2. Total number of hours accumulated (red, 0–40; orange, 40–120; yellow, 120–240; green, 240–360; blue, >360) below 12.8, 15.6, and 18.3°C during September in the southern United States.

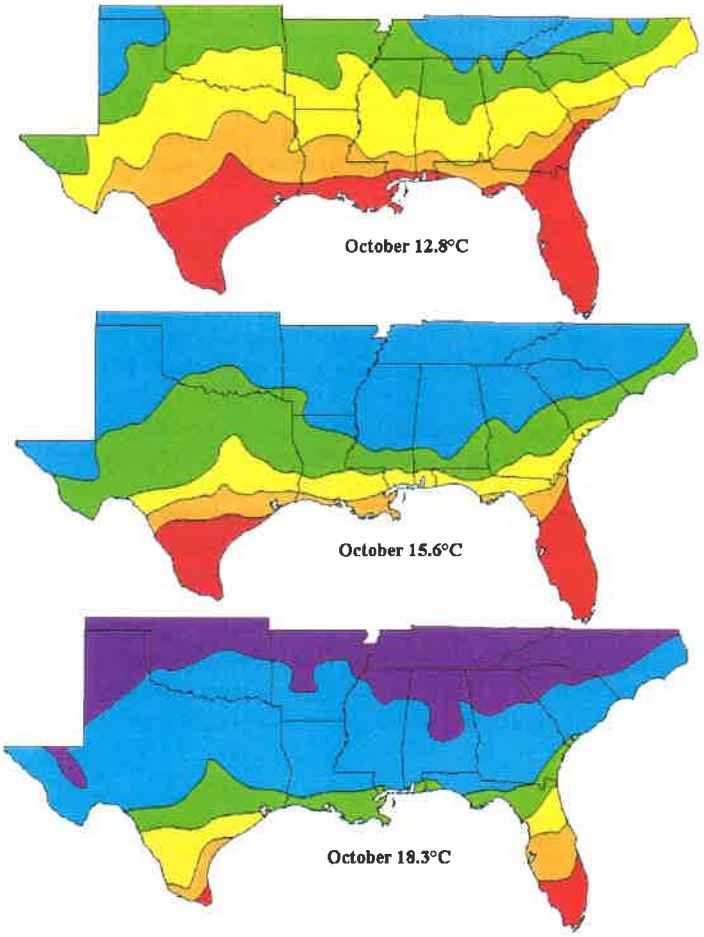

Fig. 3. Total number of hours accumulated (red, 0–40; orange, 40–120; yellow, 120–240; green, 240–360, blue, 360–480; purple, > 480) below 12.8, 15.6, and 18.3°C during October in the southern United States.

Thirty-six weather stations considered to be 1st-order airport weather stations with complete meteorological data available on Samson CD-ROM from the National Climatic Center (Asheville, NC) were grouped into 5 zones based on total hours of accumulation below 12.8°C from 1 September to 30 November. These zones were: (1) 1–175 hours, (2) 176–350 hours, (3) 351–575 hours, (4) 576–775 hours, and (5) >775 hours. For zones 1, 2, 3, and 5, additional weather stations were included to give at least 10 weather stations for each zone (Table 1). These extra stations were selected to provide a representative range within each broad geographic zone (Fig. 4).

Average dates for corn binning after harvest, based on summarized statistical data for each state, were estimated to be 24 August for zone one, 1 September for zone two, 8 September for zone three, 15 September for zone four, and 22 September for zone five. Hourly data from 1960 to 1989 from the 1st-order stations within each zone were summarized into a 12-month temperature data set for each station. A simulation model that integrated bin cooling with maize weevil development described by Maier et al. (1996) was used to predict maize weevil populations for each temperature-airflow rate combination and for corn stored with no aeration. The simulations were based on starting values of 10 adult males and 10 adult females present in a 76, 363 kg (3,000 bushel bin) at the binning date, with no subsequent reinfestation during storage. The dates by which 120, 60, and 40 hours were accumulated below threshold temperatures of 12.8, 15.6, and 18.3°C and the predicted bin temperatures after the cooling cycles were completed were averaged for each zone.

Results and Discussion

An initial activation temperature of 12.8°C would not be feasible for aerating corn stored in the southern United States because of the lack of sufficient cooling hours in September (Fig. 2). Increasing the activation temperature to 15.6°C yields an increase in accumulation hours; however, throughout most of the region the accumulat-

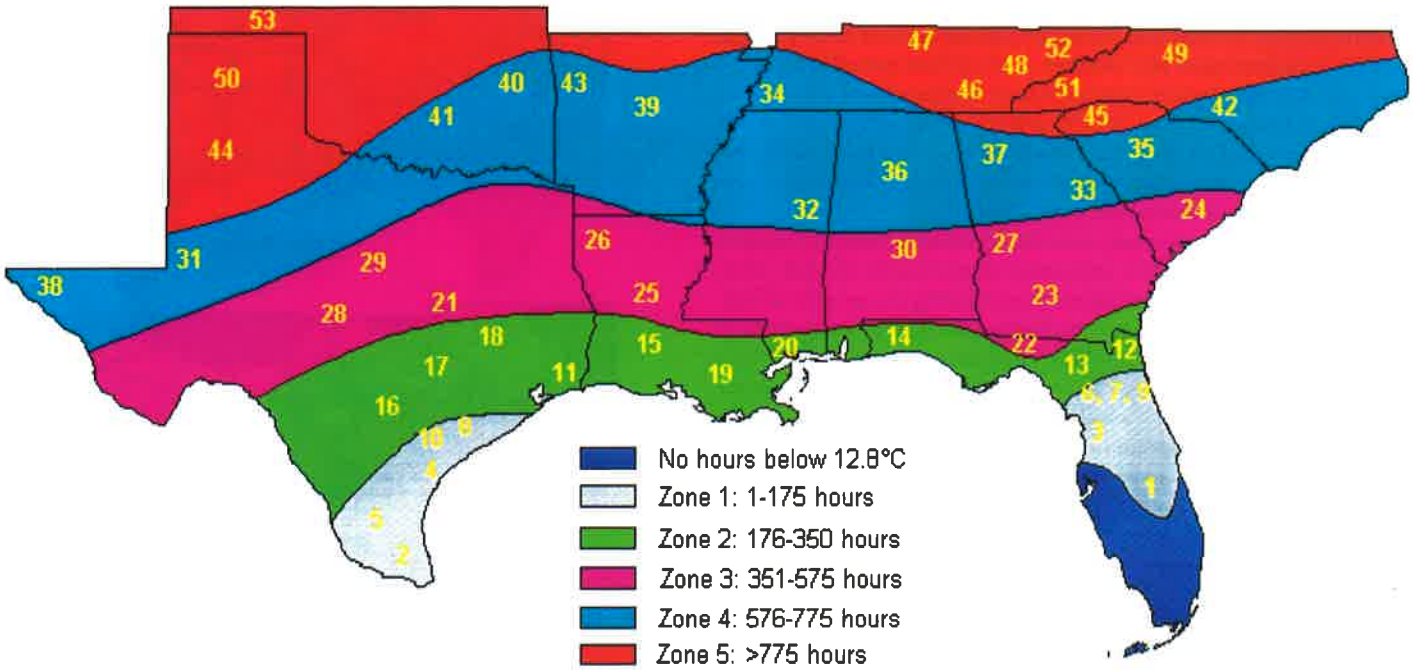

Fig. 4. Delineation of 5 zones based on total hours accumulated below 12.8°C from 1 September to 30 November. The numbers represent the approximate locations of the weather stations listed in Table 1.

Table 1. Listing of weather stations grouped into 5 zones based on the number of h below 12.8°C from 1 September to 30 November

ID no.	Station	Lat.	Long.	Total h < 12.8°C
Zone: 1				
Binning date: 24 August				
1	Avon Park, FL[a]	27° 36'	81° 32'	6
2	Weslaco, TX[a]	26° 09'	97° 58'	12
3	Brooksville, FL[a]	28° 62'	82° 37'	30
4	Corpus Christi, TX	27° 77'	97° 50'	49
5	Falfurrias, TX[a]	27° 23'	98° 13'	62
6	Inverness, FL[a]	28° 73'	82° 32'	79
7	Ocala, FL[a]	26° 11'	80° 07'	83
8	Victoria, TX	28° 51'	96° 55'	127
9	Gainesville, FL[a]	29° 63'	82° 37'	131
10	Beeville, TX[a]	28° 45'	97° 70'	156
Zone: 2				
Binning date: 1 September				
11	Port Arthur, TX[a]	29° 57'	94° 01'	189
12	Jacksonville, FL	30° 30'	94° 01'	206
13	Lake City, FL[a]	30° 18'	82° 60'	240
14	Pensacola, FL[a]	30° 28'	87° 12'	246
15	Lafayette, LA[a]	30° 20'	91° 98'	255
16	San Antonio, TX	29° 32'	98° 28'	266
17	Austin, TX	30° 17'	97° 42'	272
18	College Station, TX[a]	30° 58'	96° 37'	275
19	Baton Rouge, LA	32° 32	91° 08'	336
20	Poplarville, MS[a]	30° 85'	89° 55'	349
Zone: 3				
Binning date: 8 September				
21	Waco, TX	31° 37'	97° 13'	373
22	Tallahassee, FL	30° 23'	84° 22'	394
23	Tifton, GA[a]	31° 29'	83° 32'	415
24	Charleston, SC	32° 54'	80° 02'	426
25	Alexandria, LA[a]	31° 29'	92° 28'	436
26	Shreveport, LA	32° 28'	93° 49'	475
27	Columbus, GA	32° 31'	84° 57'	494
Zone: 3				
Binning date: 8 September (cont.)				
28	San Angelo, TX	31° 32'	100° 30'	511
29	Abilene, TX	32° 25'	99° 41'	521
30	Montgomery, AL	32° 18'	86° 24'	532
Zone: 4				
Binning date: 15 September				
31	Midland, TX	31° 57'	102° 11'	619
32	Meridian, MS	32° 20'	88° 45'	637
33	Augusta, GA	33° 22'	81° 58'	650
34	Memphis, TN	35° 03'	90° 00'	650
35	Columbia, SC	33° 57'	81° 07'	661
36	Birmingham, AL	33° 24'	86° 45'	677
37	Atlanta, GA	33° 39'	84° 26'	685
38	El Paso, TX	31° 48'	106° 24'	699
39	Little Rock, AR	34° 44'	92° 14'	704
40	Tulsa, OK	36° 12'	95° 54'	746
41	Oklahoma City, OK	35° 21'	97° 36'	748
42	Charlotte, NC	35° 13'	80° 56'	748
43	Fort Smith, AR	34° 44'	92° 41'	760
Zone: 5				
Binning date: 22 September				
44	Lubbock, TX	33° 39'	101° 49'	794
45	Greenville, SC	34° 51'	82° 41'	804
46	Chattanooga, TN	35° 02'	85° 12'	822
47	Nashville, TN	36° 07'	86° 41'	850
48	Knoxville, TN	35° 49'	83° 59'	870
49	Greensboro, NC	36° 05'	79° 57'	900
50	Amarillo, TX	35° 14'	101° 42'	965
51	Asheville, NC	35° 36'	82° 32'	1000
52	Bristol, TN	36° 29'	82° 24'	1005
53	Beaver, OK[a]	36° 49'	100° 32'	1007

Zone 1, 1–175 h; zone 2, 176–350 h; zone 3, 351–575 h; zone 4, 576–775 h; and zone 5, >775 h.
[a]These stations were not 1st-order weather stations, but were included to provide at least 10 stations for each zone.

ed hours are below the theoretical requirement of 40 that are necessary to cool a bin using an airflow rate of 0.0039 $m^3/s/m^3$ (Fig. 2). If the activation temperature is increased to 18.3°C, the necessary hours are accumulated to begin aerating corn in all parts of the south except for the Gulf and South Atlantic coasts (Fig. 2).

As temperatures cool in October, more hours below the specified activation temperatures are available for aeration. Aeration at an activation temperature of 12.8°C could be accomplished at any of the 3 proposed airflow rates, with the exception of the southernmost portion of the region (Fig. 3). However, cooling at this temperature would be accomplished more quickly in Oklahoma, Arkansas, Tennessee, and North Carolina compared to the southernmost regions of Texas, Louisiana, Mississippi, Alabama, Georgia, and north Florida. Hours of accumulation at the activation temperature of 15.6°C are increased relative to 12.8°C in all states (Fig. 3), and a cooling cycle could be completed by the end of October in all locations except southern Florida and southern Texas. Increasing the activation temperature to 18.3°C yields approximately 120 more h than the accumulations for 15.6°C in most locations (Fig. 3).

Results for the model simulations with the 1st-order weather stations in each zone (Fig. 4) show how accumulation dates are advanced when the activation temperature increases from 12.8 to 15.6 to 18.3°C and as the hours required for completion of the cooling cycle decrease from 120 to 40 (Table 2). However, the model indicates that the average bin temperatures are always warmer than the activation temperatures at the completion of the cycles. Unexpectedly, even though cooling cycles in each zone are completed more quickly as airflow rates increase, the predicted maize weevil populations after 1 yr of storage often were lower in the 120-h cooling cycles than in the 60 and 40-h cycles at the activation temperatures of 15.6 and 18.6°C (Table 2).

The average bin temperatures at the completion of aeration were similar at all 3 cooling cycles, yet decreasing the time required to complete a cooling cycle at activation temperatures of 12.8 and 15.6°C did not result in a corresponding decrease in maize weevil populations. The impact of aeration on maize weevil development within each zone is illustrated by comparing predicted populations per bushel at an airflow rate of 0.0013 $m^3/s/m^3$ to the predicted pop-

Table 2. Date by which the model predicted 120, 60, and 40 h would be accumulated below temperatures of 12.8, 15.6, and 18.3°C for the 1st-order weather stations listed in Table 1, the average grain temperature at the end of the aeration cycle, and the estimated number of maize weevils after 1 yr of storage

Zone[a]	Activation temp.	Time below threshold, h	Date cycle completed	Average bin temp.	No. of maize weevils after 1 yr
1	12.8	120	12/13	14.6	10,275,550
		60	12/08	14.2	8,921,700
		40	12/04	13.8	9,649,500
	15.6	120	11/25	17.1	5,860,550
		60	11/19	17.6	5,668,100
		40	11/15	17.3	4,472,900
	18.3	120	11/05	19.9	4,297,250
		60	10/30	20.3	5,104,450
		40	10/27	20.7	8,970,150
2	12.8	120	11/25	14.9	1,967,475
		60	11/17	14.8	1,920,207
		40	11/13	14.9	1,468,662
	15.6	120	11/07	17.1	1,203,800
		60	11/01	18.0	1,627,500
		40	10/28	17.6	1,403,885
	18.3	120	10/22	19.8	1,599,305
		60	10/16	20.7	2,228,457
		40	10/13	20.6	2,953,450
3	12.8	120	11/12	14.4	433,361
		60	11/05	15.0	437,626
		40	11/03	14.9	400,310
	15.6	120	10/27	17.5	298,610
		60	10/21	17.6	263,987
		40	10/19	17.9	301,056
	18.3	120	10/13	19.6	237,787
		60	10/07	19.9	269,618
		40	10/05	20.2	767,203
4	12.8	120	10/31	14.3	61,251
		60	10/25	14.7	56,715
		40	10/22	14.7	55,015
	15.6	120	10/17	17.4	48,246
		60	10/10	17.1	53,082
		40	10/07	17.1	51,647
	18.3	20	10/05	19.6	77,970
		60	09/29	19.9	105,542
		40	09/27	19.9	113,931
5	12.8	120	10/21	14.2	5,936
		60	10/13	15.0	4,583
		40	10/10	14.9	4,327
	15.6	120	10/08	17.0	3,710
		60	10/02	17.5	4,995
		40	09/30	17.5	5,995
	18.3	120	10/02	19.0	7,689
		60	09/27	18.8	8,447
		40	09/26	18.0	8,713

All simulations were run with 10 adult males and 10 adult females infesting the corn on the binning dates, which were 24 August, 1 September, 8 September, 15 September, and 22 September, for zones 1, 2, 3, 4, and 5, respectively.

[a]Zone 1, 1–175 h; zone 2, 176–350 h; zone 3, 351–575 h; zone 4, 576–775 h; and zone 5, > 775 h accumulated below 12.8°C from 1 September to 30 November.

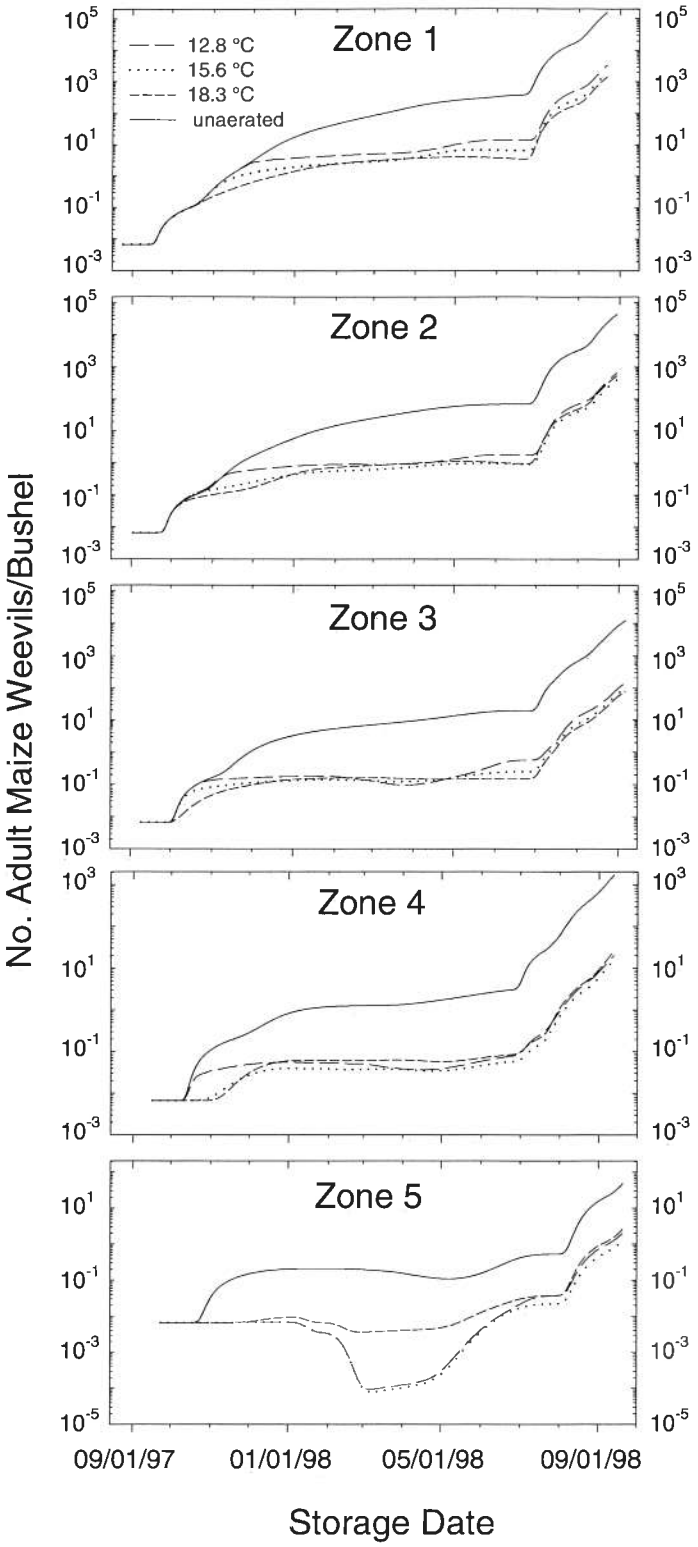

Fig. 5. Predicted maize weevil populations per bushel in unaerated and aerated corn stored in zones 1–5 with aeration activation temperatures of 12.8, 18.6, and 18.3°C, and an airflow rate of 0.0013 $m^3/s/m^3$ (0.1 cubic ft per minute per bushel) (see Fig. 4 for description of zones).

ulations in unaerated corn (Fig. 5). Values on the Y-axis for each zone graph are numbers of maize weevils per bushel of corn, on a logarithmic scale.

Corn stored in zones 1, 2, and 3 may require management inputs in addition to aeration to control maize weevils (Fig. 5). Although the predicted populations are lower as the zones progress northward from zone 1 to zone 3, the patterns of growth and development in aerated and unaerated corn are similar for all 3 zones. Maize weevil populations at the beginning of the next calendar year (1 January 1998) will be greatest in corn that is aerated at an activation temperature of 18.3°C; however the number of maize weevils in corn aerated at all 3 activation temperatures is considerably fewer than the number in unaerated corn. Weevil populations in aerated corn increase slightly from 1 January 1998 to 1 July 1998, whereas the populations in unaerated corn increase at a much faster rate. However, the patterns of increase will be similar in aerated and unaerated corn after 1 July 1998. Although aeration has an obvious impact on the maize weevil populations, the numbers that will be produced after the binning date in zones 1, 2, and 3 may be too excessive to manage stored corn using aeration alone without any chemical controls.

An activation temperature of 15.6 or 18.3°C could be used for aerating corn stored in zone 4, whereas any of the 3 activation temperatures could be used for zone 5. Maize weevil populations in aerated corn in both zones would remain low until 1 July 1998. Populations in unaerated corn will increase from the binning date to 1 February 1998, and then remain relatively stable until 1 July 1998. Weevil populations in aerated and unaerated corn will increase after 1 July 1998; therefore, corn stored after this time may require chemical inputs.

The results of this simulation study show that aeration could be used to manage maize weevils stored in the southern United States, but specific recommendations may be required for corn stored in different temperature zones. An aeration cycle using an activation temperature of 12.8°C cannot be completed in time to prevent the establishment of a partial or even complete fall generation of maize weevils in most of the southern United States. An activation temperature of 15.6°C would be better than 18.3°C because 15.6°C is nearer the lower developmental level for maize weevils (Throne 1994). Winter temperatures normally are not cold enough to kill maize weevils in stored corn, therefore populations will develop rather quickly once temperatures warm up in the spring and summer (Arbogast and Throne 1997).

An airflow rate of 0.0013 $m^3/s/m^3$ appears to be the optimum airflow rate for aeration management at an activation temperature of 15.6°C, because increasing the airflow rates did not yield a corresponding decrease in maize weevil populations (Table 2). However, aeration alone may not control maize weevil populations, particularly in warm-weather sites with early harvest dates. Nonchemical control strategies, such as varietal resistance and moisture management, can alter life history parameters and reduce population growth (Throne 1989). These tactics could be integrated with aeration to reduce the number of chemical applications required to effectively manage stored corn or avoid them altogether.

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