Feasibility of Summer Aeration to Control Insects in Stored Wheat

F. H. Arthur, M. E. Casada

Abstract. *Temperature profiles and insect populations were compared in wheat that had been aerated with low airflow rates during the summer in addition to two autumn aeration cycles, versus wheat aerated in autumn only or unaerated wheat. Tests were conducted in 2000-2001, 2001-2002, and 2002-2003, and data were analyzed separately for each year. Grain mass temperature profiles at depths of 0.9 and 1.8 m from the surface in the grain mass showed distinct declines in temperature for each aeration cycle during the first two years of the study, however, summer aeration did not result in as large of temperature declines in 2002-2003, partly because the summer aerated bin was loaded with warmer grain. The effectiveness of summer aeration was estimated using confined insect populations in tube cages placed on the surface of the grain and by sampling the grain for natural insect populations using pitfall probe traps. At the conclusion of the summer aeration cycle, the number of lesser grain borer,* Rhyzopertha dominica *(Fabricius), red flour beetle,* Tribolium castaneum *(Herbst), and rice weevil,* Sitophilus oryzae *(L.) in the tube cages were consistently lower in bins that had not been aerated during the summer. Pitfall trap catch of rusty grain beetles,* Cryptolestes ferrugineus *(Stephens), hairy fungus beetle,* Typhaea stercorea *(L.), foreign grain beetle,* Ahasverus advena *(Walt), and lesser grain borer was consistently lower in bins with summer aeration, indicating a reduction in natural insect populations. Field data support modeling simulation studies that predict lower insect populations when a summer aeration cycle is included.*

Keywords. *Wheat, Storage, Insects, Management.*

Hard red winter wheat is harvested and stored in the central plains of the United States in June or July, depending on planting date, environmental conditions, and moisture at the time of harvest. This wheat is susceptible to damage by a variety of insect pests, and normally temperatures during the summer are in the range of 27°C to 33°C (80°F to 95°F), which are conducive to insect growth and development (Howe, 1965; Fields, 1992). Once temperatures begin to decline in autumn, the grain mass will slowly cool to levels that will not support insect growth (Sun and Woods, 1994ab; Jia et al., 2001), which is about 15°C (60°F) for most stored-grain insects (Fields, 1992).

Aeration with ambient air is often used to help manage stored wheat in the midwestern United States by cooling the grain (Cuperus et al., 1986, 1990; Harner and Hagstrum, 1990; Hagstrum et al., 1999). Airflow rates used for aeration are typically 0.11 m^3/min/t (0.1 ft^3/min/bushel, cfm/bu) or less, while rates used for drying are much higher, and can also involve the use of heated air (Reed and Arthur, 2000). Aeration can be controlled manually or by using discrete cycles below specified temperature thresholds, with the aid of automatic controllers (Reed and Harner, 1998ab). Air movement through a grain mass is a function of airflow rate (Harner and Hagstrum, 1990). At an airflow rate of 0.11 m^3/min/t, 120 h below a given temperature threshold are typically required to cool a wheat mass to that temperature, and as the airflow rates increase to 0.22 and 0.33 m^3/min/t, the hours required for cooling drop to 60 and 40 h, respectively (McCune et al., 1963; Noyes et al., 1992). These time requirements for the different airflow rates are often referred to as "aeration cycles."

Typical recommendations state that an early autumn cooling cycle to 15°C should be used for stored wheat, followed by a late autumn cooling cycle to 7.2°C (Noyes et al., 1992). Simulation studies based on insect population models and heat transfer bin-cooling models predict that a summer aeration cycle of 23.7°C (75°F), using an airflow rate of 0.11 m^3/min/t, would reduce insect populations in wheat stored in Kansas (Flinn et al., 1997). Reed and Harner (1988ab) conducted studies in which the addition of a summer aeration cycle was compared to aeration in early and late autumn only. In these field trials, aeration was done at 0.22 m^3/min/t or more, and at this rate insect populations were reduced in those bins where the 3-cycle approach was used.

Modeling and temperature accumulation studies show that there are sufficient hours in Kansas for an initial cooling of 23.7°C in early summer, using an airflow rate of 0.11 m^3/min/t (Arthur and Flinn, 2000). However, there are no field studies where this low rate has been evaluated during a multi-year period. Therefore, the first objective of this study was to conduct a field validation test by evaluating three temperature management strategies: 1) no aeration, 2)

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controlled aeration at 15°C (60°F) in early autumn and 7.2°C (45°F) in late autumn, the standard two-cycle cooling regimes currently used for stored wheat, and 3) controlled aeration at 23.7°C immediately after binning, followed by the standard autumn cooling cycles. Grain management is often a function of temperature management, and although there are many systems developed to monitor temperatures in grain bins, many of the less expensive systems do not record temperatures, and those that do may not be economical for on-farm use. There are several new products that can record temperature data that is then downloaded to a personal computer, and may be suitable for small-scale use. A second objective was to use one of these systems, HOBO data loggers manufactured by Onset Computers (Bourne, Mass.), to demonstrate an inexpensive and simple method to record temperatures inside bulk stored wheat. The final objective was to determine the efficacy of the aeration strategies by monitoring insect populations through natural and artificial infestations.

Materials and Methods

This study was conducted in three steel bins at the Grain Marketing and Production Research Center (GMPRC), Manhattan, Kansas, in 2000-2001, 2001-2002, and 2002-2003. The bins were 6.6 m diameter, 4.2 m to the eave height, and 6.0 m to the peak height, and had a full capacity of approximately 109,090 kg (4,000 bu). Each year, new crop wheat was purchased from a local commercial elevator, delivered by semi-trailer, and loaded into the pilot elevator at the GMPRC. The wheat was held for a week and then transferred by truck to the three bins, and this process usually took 2-3 days to complete. In the first year the bins were filled to a height of about 3.7 m (12 ft), ca. 95,454 kg, and to a height of 2.7 m (9 ft), ca. 73, 482 kg for the last two years, respectively. In 2000-2001 and 2001-2002, three treatments were evaluated: (1) control (no aeration), (2) early and late autumn aeration 15°C and 7.2°C, respectively, and (3) aeration to 23.7°C immediately after binning, followed by autumn aeration. In 2002-2003 only treatments 2 and 3 were done because of extensive natural insect infestations in the control bin during the previous year. The damage was so severe that although the wheat had been fumigated it was severely discounted when returned, which was very costly. Also, because the wheat bins were near the property line of our center, proposed new label restrictions for the fumigant phosphine could have posed some limits for fumigations at our site. Consequently, the risk of economic damage in a bin that was unaerated and at risk for fumigation was not assumed, so in 2002-2003 an unaerated bin was not included in the study.

Aeration fans were set to cool the wheat at 0.11 m^3/min/t (0.1 cfm/bu) during the first year, and a controller on the bins was set to turn the fans on when temperatures fell below the desired set points. The wheat depths during the second and third years resulted in airflow rates of 0.14 and 0.19 m^3/min/t (0.13 and 0.17 cfm/bu) in the summer aerated and non-summer aerated bins, respectively. Fans were turned off and the aeration ducts were sealed with heavy-duty plastic sheeting to restrict air movement into the bins after each cooling front had passed through the grain mass. The ducts were unsealed when weather forecasts were predicting a temperature decrease to the next aeration cycle; when the final cycle was complete the fans were sealed for the duration of the study for a particular year.

New crop wheat was augured into each of the three bins separately and loading was completed on 11, 12, and 15 July in 2000, 2001, and 2002, respectively. After all bins were filled, the wheat mass in each bin was leveled and three HOBO recording data loggers (H-8 series, 4-channel, Onset Computers, Bourne, Mass.) were put on the surface of the wheat in the north, south, and center positions. Cables were attached to each data logger with a temperature sensor on the end, and these cables were used to record temperatures at depths of 0.30, 0.92, and 1.85 m (1, 3, and 6 ft) from the surface within the grain mass (12 cables in each bin). The data loggers and cables at the north and south positions were set approximately 0.30 to 0.60 m from the side walls. A modified flange attached to the end of a standard grain probe was used to push the cable and the temperature sensor down to the desired depth. A modified cylindrical metal flange with slots on either side was attached to the end of a standard grain probe. The cable fit in the slots of the flange and the probe was used to push the cable and the temperature sensor down to the desired depth. The data loggers were set to record temperatures at hourly intervals, and data from each logger was downloaded approximately every two weeks until the final cycle was completed, then read at monthly intervals during the winter, weather permitting, until the wheat was unloaded from the bin. A HOBO Shuttle was used to download data from individual loggers and transfer the files to a personal computer.

Plastic insect cages containing 30 gm of wheat, of which 10% consisted of cracked and broken wheat, were prepared for insertion into the experimental bins. These cages were plastic cylindrical tubes approximately 0.31 m long and inside diameter of 1.3 cm, with several rows of 1-mm holes in the side for air exchange. Individual cages were seeded with 10 mixed-sex adults of either the lesser grain borer, *Rhyzopertha dominica* (Fabricius), the rice weevil, *Sitophilus oryzae* (L.), or the red flour beetle *Tribolium castaneum* (Herbst) (one set). Each set of three cages was tied together, and the end of the string was long enough to lay on the surface of the wheat and mark the position of the cages. After the temperature cables were placed in the bins, one set of cages was placed at a depth of 0.026 m and a second group was placed at a depth of 0.31 m, in the approximate position of the HOBO sensor at each of those positions. The cages were laid horizontally in the wheat. After the first aeration cycle was completed the cages were removed from each bin, and the wheat was sifted and the number of adults of each species was recorded. The wheat from the cages containing the lesser grain borer and the rice weevil was put into individual half-pint jars and held at 27°C for 8 weeks to collect adults emerging from the kernels. Before the second aeration cycle was initiated, a new set of cages was prepared and put into the bins, which was subsequently removed upon completion of the cycle, and the number of insects were recorded and tabulated as described above. A final set of cages was put into the bin at the start of the third cooling cycle in late autumn, and insect numbers were recorded and tabulated following the same procedures as previously described.

The wheat bins were also sampled for natural insect populations at monthly intervals by placing pitfall traps just below the surface of the wheat in the north, south, east, and west positions, about 0.30 to 0.60 m from the side walls and at the center position. Traps were put inside the bins for one week, then removed and the following insect species were tabulated: rusty grain beetle *Cryptolestes ferrugineus* (Stephens), hairy fungus beetle, *Typhaea stercorea* (L.), foreign grain beetle, *Ahasverus advena* (Walt), red flour beetle, and lesser grain borer. The data profiles from the HOBOs were used to analyze temperatures at each of the sensor points and bin depths for each of the aeration treatments. Accuracy data acquisition for the HOBO loggers as specified on the Onset computer Web site (www.onsetcomputer.com) is ±0.7% at 21°C. These data and the insect population data from the inserted cages and the probe traps were used to compare treatments in each of the storage years. Because of variation among the individual years, data for the insect cages and the insect probe traps were analyzed separately for each year, using Chi-Square analysis (SAS Institute, 2002) to determine differences among the three aeration treatment regimes.

Results

Temperature Profiles

2000-2001

Average daily ambient temperature at the start of the test was 35°C, then gradually decreased to a fluctuating level of about 25°C to a little over 30°C until September (fig. 1A). Temperatures gradually cooled during September to a low point of 5°C to 7°C, which was unusually cool for Kansas during that time of the year. Temperatures then increased, followed by another temperature drop in October with a subsequent increase until the end of October. A gradual cooling to a low of -15°C in late December was evident, and beginning in early January there was a general increase in ambient temperature, with a fluctuating pattern that was consistent with daily average temperature recordings.

The average temperature for each location in the aerated bins was calculated for an approximate 2-month period after summer aeration was initiated but before autumn aeration began (table 1). The average cooling near the top of the bin was about 2°C but was in excess of 5°C in some locations deeper in the bin. An exception was the north side at 0.9 m depth, which showed no cooling compared to the bin that was not yet aerated.

Temperature profiles of the north position at 0.3 m (fig. 1B) throughout the season were similar among all three aeration regimes, no aeration (solid line), autumn aeration only (dotted line), and summer aeration in addition to autumn aeration (dashed line). This position was about 0.31 to 0.46 m from the bin wall, and temperatures at this point reflected the pattern of the ambient temperature, although the fluctuations were somewhat dampened. The profiles at the center position at 0.3 m (fig. 1C) were more variable, in general they were greatest in the unaerated bin, and were lower in the bin with summer aeration compared to autumn aeration only. The two autumn aeration cycles were evident in the sharp temperature declines in the two aerated bins, in contrast to the fluctuating temperatures in the unaerated bin. In February there was an increase in the temperatures in the bin with autumn aeration only, which may have been a reflection of the insect activity, which will be discussed in the subsequent section. The temperature profiles of the south position at a depth of 0.3 m (fig. 1D) were similar among the three aeration regimes, except for an unexplained decline from about 1 November to the end of the year in the bin with autumn aeration.

At 0.9 m there was a dampening of extreme temperatures consistent with the insulating effects of a grain mass. Temperatures at the north position (fig. 1E) of the unaerated bin, again 0.31 to 0.62 m from the bin wall, gradually declined to a low of between 0°C and 5°C, remained at this level until 1 March, then began to increase as ambient temperatures increased. Temperatures in both of the aerated bins were generally lower than in the unaerated bin, with a small difference in the summer and autumn temperature profiles. There were indications of a temperature drop with autumn aeration, but the fluctuations in temperature masked this effect. In contrast, there was a difference in all three aeration regimes at the center position (fig. 1F). Temperatures during July and August were lower in the bin with summer aeration compared to the other two bins. The controller had been set to activate the fan whenever temperatures fell below 15°C, but there was a period of about five days when low temperatures were near 0°C. This caused temperatures to decline to about 10°C by the beginning of October. The subsequent second aeration cycle, in which the controller was set at 7.2°C, produced a much smaller decline in temperature compared to the first cycle. The patterns in the south position at a depth of 0.9 m (fig. 1G) were slightly different from those at the north position. There was a temperature decline during summer in the bin with the additional summer aeration cycle, fluctuations in the two autumn aeration cycles were somewhat dampened, and there were distinct temperature declines in mid-September and mid-October that coincided with the aeration cycles, and the lowest temperatures in the aerated bins during the winter months were similar to the temperatures in the center position.

Temperature patterns in the north position at 1.8 m (fig. 1H) were much different than those at the north position depths of 0.3 and 0.9 m, which reflected the insulating effects of the grain mass. The temperature in the unaerated bin was about 30°C until November, declined to 20°C during the winter months, then began to increase at the first of March. The effects of the summer aeration cycle were apparent, along with the two distinct temperature declines in September and August. Winter temperatures in the aerated bins were about 0°C, and were distinctly lower than in the unaerated bin. In the center position at 1.8 m (fig. 1I), there was a gradual temperature decline from October until April in the unaerated bins, and temperature declines in two aerated bins were similar to the patterns in figure 1H. In contrast, the temperature profiles at the south position (fig. 1J) were extremely unusual in that the grain temperature in the bin with autumn aeration only was 30°C to 40°C for most of the year. This was likely due to an extensive insect infestation or hotspot at that location which contributed to the elevated temperatures.

2001-2002

Ambient temperatures during July and August were between 25°C and 35°C, except for one cool spike in early August (fig. 2A). Temperatures began to cool gradually during September, as contrasted with the previous year in

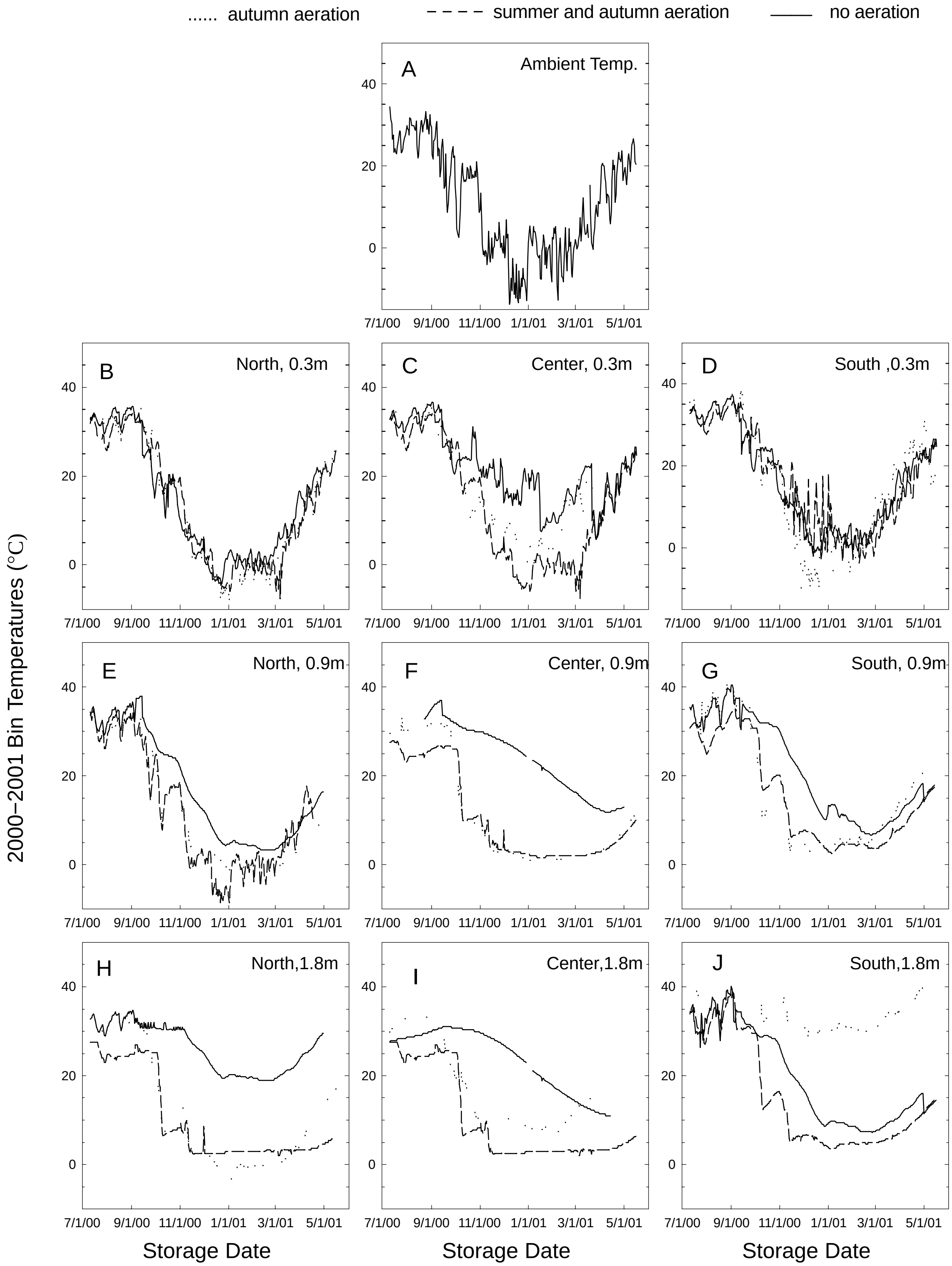

Figure 1. Temperature profiles in 2000-2001 at three positions and depths of 0.3, 0.9, and 1.8 m in wheat aerated twice during autumn, aerated during the summer in addition to aeration in autumn, or unaerated.

which there was an unusual cold spell in mid-late September. Cooling patterns continued until January, and after the first of the year temperatures fluctuated with several abrupt declines followed by a gradual increase until termination of the test in early March.

Cooling in the summer aerated bin, compared to the autumn aeration bin that was not yet being cooled, was a little more uniform than it had been the previous year (table 1). The average for the bin was almost the same as the first year (3.8°C versus 3.7°C), but the range was only from 2.1°C to 5.9°C. In the previous year, the range was -0.4°C to 7.2°C, and the 0.3m depth had noticeably less cooling than the deepr parts of the bin. This year the main depth effect was at the

Table 1. Average temperatures and cooling, compared to bins not aerated in summer, from summer aeration for the two-month period directly affected by summer aeration during the three-year study.

		11 July to 15 Sept. 2000			12 July to 16 Sept. 2001			17 July to 21 Sept. 2002		
		AA (°C)[a]	SA + AA (°C)[b]	Cooling (°C)	AA (°C)	SA + AA (°C)	Cooling (°C)	AA (°C)	SA + AA (°C)	Cooling (°C)
0.3m	N	32.8	31.3	1.5	32.8	28.4	4.4	29.9	28.2	1.7
	C	33.4	31.3	2.1	33.7	30.1	3.6	31.3	28.3	3.0
	S	34.4	32.4	2.0	33.7	31.6	2.1	32.2	30.8	1.4
0.9m	N	30.7	31.1	-0.4	31.7	26.9	4.8	29.3	26.7	2.6
	C	30.9	25.6	5.3	32.0	26.1	5.9	30.3	26.5	3.8
	S	36.5	30.6	5.9	33.9	30.1	3.8	31.8	27.9	3.9
1.8m	N	30.7	25.1	5.6	30.4	27.7	2.7	28.2	24.5	3.7
	C	32.8	25.6	7.2	30.3	25.7	4.6	29.4	25.3	4.1
	S	−	33.0	−	32.6	30.1	2.5	31.3	28.2	3.1
Annual Avg.		32.8	29.6	3.7	32.3	28.5	3.8	30.4	27.4	3.0

[a] AA = autumn aeration only.
[b] SA + AA = summer aeration plus autumn aeration.

0.9-m position, where temperatures were slightly cooler than at the other two depths.

Temperature profiles in the bins throughout the storage season were slightly different from the profiles in the first year of the study, including those of the surface position at a depth of 0.3 m. The unaerated bin became heavily infested in autumn, and in contrast to the previous year, this bin was not fumigated. This extensive infestation persisted during the winter months, and as a result the temperatures in this bin did not cool during the winter except at the north position, 0.3 m. In all three bins, the temperatures at the north position (fig. 2B) seemed to fluctuate and reflect the ambient temperature during the summer months. Cooling cycles in September and November were evident, as shown by the lines for the bins with summer and autumn aeration (dashed line) and the bin with autumn aeration only. The temperature at the comparable position in the unaerated bin declined in a somewhat gradual trend marked by fluctuations until early January, then afterwards began to increase during the winter months. The temperature profiles at the center position (fig 2C) in the unaerated bin and the bin with autumn aeration only fluctuated extremely. There was no clear pattern or aeration effect in the bin with autumn aeration only, except for a brief downward trend in September. Temperatures in the unaerated bin were generally above 20°C until early January, then began rapidly increasing until the conclusion of the test. Distinct temperature drops corresponding to the aeration cycles were evident in the bin with summer aeration in addition to autumn aeration, but there is no sufficient explanation as to why this pattern did not also occur in the bin with autumn aeration only. Temperatures at the south position seemed to correspond to the aeration cycles. Temperatures in the unaerated bin remained above 30°C for most of the year, and approached 40°C in January and February 2002.

As in the previous year, the aeration effects were more distinct at the depth of 0.9 m as compared to 0.3 m. At the north position (fig. 2E), temperature dropped as a result of summer aeration, but increased until the first aeration cycle. In both bins with autumn aeration, the two distinct drops in temperature corresponded to the aeration cycles. The temperature in the unaerated bin gradually decreased to below 20°C by January, but then sharply increased until the test was concluded. In contrast, the temperature in the unaerated bin at the center position (fig. 2F) was about 40°C from October through March. Summer aeration lowered the temperature at this center position to about 25°C, and trends for all three bins were similar at the south position to those in the center position (fig. 2G).

The effects of summer aeration were also apparent at the depth of 1.8 m. At the north position (fig. 2H), summer aeration produced an initial decline in temperature, but temperatures quickly increased before stabilizing at about 25°C in August. The two cooling cycles were evident in the bins with autumn aeration, while in contrast the temperature at the north position in the unaerated bin remained above 20°C until January. Trends for the center (fig. 2I) and south positions (fig. 2J) were similar to the trends observed at a depth of 0.9 m, especially the extremely elevated temperatures in the unaerated bin.

2002-2003

As stated previously, there was no unaerated bin this year partly because of the extensive damage in unaerated wheat during the previous year. Average daily ambient temperatures were again between 25°C and 35°C in July and August, except for one period where temperatures were about 20°C (fig. 3A). As in the previous year, temperatures began to gradually cool in September, with a brief warm period near the end of the month, then began to gradually cool until January, followed by eventual warming in 2003.

Cooling in the summer aerated bin during the first two months showed a pattern similar to the first year−−less cooling at the top than deeper in the bin. The magnitude of the differences with depth was less this year than the first year and, overall, temperatures were more uniform this year than even during the second year. The range of cooing effects was only from 1.4°C to 4.1°C this year and the average cooling for the whole bin was the least of all three years at 3.0°C (table 1).

Temperature profiles in the bins during the storage season were different than in the previous year in that there appeared to be less difference between the two aeration strategies. Temperature patterns were similar at a depth of 0.3 m in the north, center, and south positions (figs. 3B, C, D), and in the north position at 0.9 m (fig. 3E). There was less reduction in temperature in the bin with summer aeration at the center and south positions, (figs. 3F, G, respectively), compared to previous years. This may have been due to the initial grain

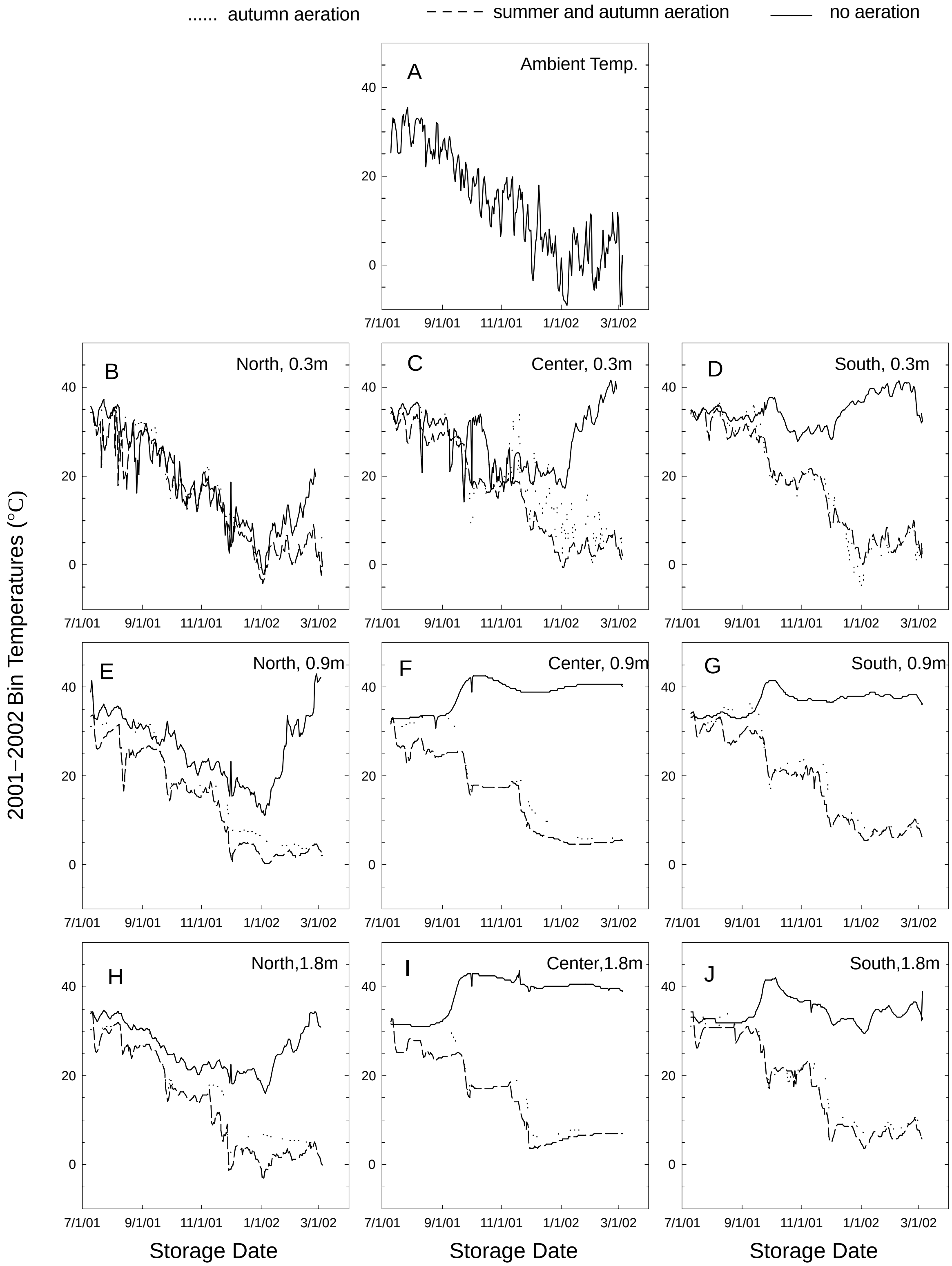

Figure 2. Temperature profiles in 2001-2002 at three positions and depths of 0.3, 0.9, and 1.8 m in wheat aerated twice during autumn, aerated during the summer in addition to aeration in autumn, or unaerated.

temperatures. The initial grain temperature in the summer aerated bin was about 5°C greater than in the autumn aerated bin (figs. 3E through J). Similar results were obtained for the 1.8-m depth at the north position for both aeration strategies (fig. 3H). The temperatures at the center and south positions (figs. 3I and J, respectively) were lower than in the previous two years, possibly because of the high initial temperature. The cooling cycles during autumn were more distinct in the bin with autumn aeration only than in the bin with the additional summer aeration.

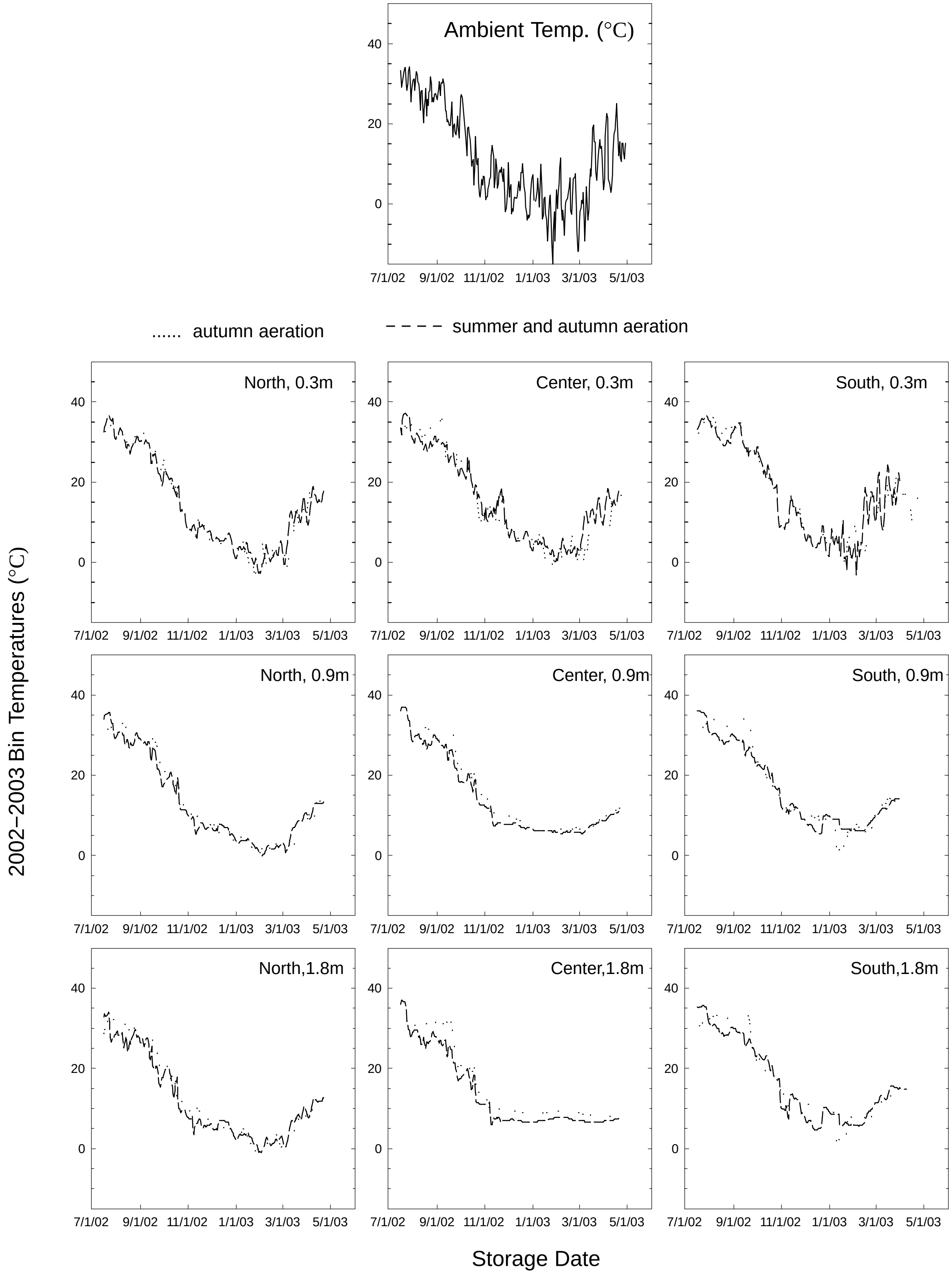

Figure 3. Temperature profiles in 2002-2003 at three positions and depths of 0.3, 0.9, and 1.8 m in wheat aerated twice during autumn or aerated during the summer in addition to aeration in autumn.

INSECT INFESTATIONS AND ACTIVITY

2000–2001

Populations in the insect tube cages were assessed after the summer aeration cycle. With the exception of the north and south positions at 0.31 m, the number of lesser grain borers was greater in the tube cages in the bin with summer aeration than in the tube cages from the bin that was not aerated until autumn (table 2). Populations of red flour beetles were greater in the bins with summer aeration on only two occasions, but the most striking difference was the fact that few live rice weevils were found in tubes from the bin that were not aerated in the summer. Extensive populations were

Table 2. Number of live lesser grain borers, red flour beetles, and rice weevils recovered after the summer aeration cycle in 2000-2001 from insect cage tubes placed at three positions, north (N), center (C), and south (S) positions.

Location	Position[a]	Bin	Lesser Grain Borer	Red Flour Beetle	Rice Weevil
N	0.08 m	SA + AA	645	61	195
		AA	540[b]	66	1[b]
		NA	330	25	5
	0.31 m	SA + AA	475[c]	44	147
		AA	517	33	1[b]
		NA	193	127	4
C	0.08 m	SA + AA	580	83	101
		AA	430[b]	44[b]	0[b]
		NA	292	16	0
	0.31 m	SA + AA	678	73	315
		AA	400[b]	62	0[b]
		NA	486	75	0
S	0.08 m	SA + AA	730	66	11
		AA	390[b]	34[b]	0
		NA	330	17	0
	0.31 m	SA + AA	335	103	260
		AA	350	86	0[b]
		NA	230	59	0

[a] Two sets of cages of each species were put at each position (20 insects per cage) at depths of 0.08 and 0.31 m below the surface of the wheat in bins with summer aeration in addition to autumn aeration (SA + AA), autumn aeration only (AA), or no aeration (NA). Data summed for the two sets of cages, analyses made between bins SA + AA and AA.

[b] Significantly fewer live insects of each species, within each position and depth, in cage tubes from bin AA compared to cage tubes from bin SA + AA ($P < 0.05$, Chi-Square Analysis).

[c] Significantly fewer live insects of each species, at each position and depth, in cage tubes from bin SA + AA compared to cage tubes from bin AA ($P < 0.05$, Chi-Square Analysis).

found in tubes from the bin that had been aerated during the summer. One possible explanation is that the surface temperatures in the unaerated bin were high enough to inhibit insect development, while aeration effectively lowered the surface temperatures along with the overall temperatures within the bulk mass. At the conclusion of the second aeration cycle, parent insects were still alive in the tubes but there were no F_1 adults, therefore data were combined for the three positions at the depths of 0.08 and 0.31 m (table 3). In contrast to the first cycle, live rice weevils were found in all tubes. Upon completion of the third aeration cycle, no live insects were found in any of the tubes.

Data from the probe traps showed mixed effects of summer aeration. The number of rusty grain beetles, foreign grain beetles, and hairy fungus beetles were lower in July in probe traps from the bin with summer aeration than in the traps from the bin with autumn aeration only (table 4). The same result occurred in August for these species, along with the red flour beetle, but in September red flour beetle numbers were lower in traps from the bin with autumn aeration only than in traps from the bin with summer aeration. Trap catches of rusty grain beetle, red flour beetle, and the lesser grain borer were lower in the bin with summer aeration compared to autumn aeration, but the reverse was true for the foreign grain beetle and the hairy fungus beetle. Mixed results were also observed in November.

Table 3. Number of live lesser grain borers, red flour beetles, and rice weevils recovered after the first autumn aeration cycle in 2000-2001 from insect cage tubes placed at three positions, north (N), center (C), and south (S) positions.

Position[a]	Bin	Lesser Grain Borer	Red Flour Beetle	Rice Weevil
0.08 m	SA + AA	60	60	57
	AA	59	59	60
	NA	60	59	50
0.31 m	SA + AA	60	57	56
	AA	60	56	56
	NA	59	54	54

[a] Two sets of cages of each species were put at each position (20 insects per cage) at depths of 0.08 and 0.31 m below the surface of the wheat in bins with summer aeration in addition to autumn aeration (SA + AA), autumn aeration only (AA), or no aeration (NA). Data summed for all three positions at each depth for each bin, no differences ($P > 0.05$, Chi-Square Analysis) in live insects between bins AA and SA + AA.

2001–2002

In contrast to the previous year, in most instances where comparisons were significant, there were fewer lesser grain borers and red flour beetles from the insect cages in bins with summer aeration than from bins with autumn aeration only (table 5). Also, the numbers of rice weevils were much lower than in the previous year, even in the bins with autumn aeration only, which could be a reflection of the surface

Table 4. Total number of live rusty grain beetles, foreign grain beetles, hairy fungus beetles, red flour beetles, and lesser grain borers recovered in 2000-2001 from pitfall traps placed on the surface of wheat at the north, south, east, west, and center positions in bins aerated in summer plus standard autumn aeration (SA + AA), autumn aeration only (AA), or no aeration (NA).[a]

Treatment	Rusty Grain Beetle	Foreign Grain Beetle	Hairy Fungus Beetle	Red Flour Beetle	Lesser Grain Borer
July					
SA + AA	36	153[b]	16[b]	1	0
AA	44	294	86	0	0
NA	103	124	9	1	0
Aug.					
SA + AA	171[a]	33[b]	38[b]	85[b]	0
AA	656	116	76	122	0
NA	570	165	13	80	0
Sept.					
SA + AA	592[b]	112	15[b]	924	41[b]
AA	3259	126	33	431[c]	273
NA	3261	509	4	2971	142
Oct.					
SA + AA	976[b]	178	1[b]	422[b]	280[b]
AA	1698	42[c]	23	1293	504
NA	129	14	1	15	129
Nov.					
SA + AA	434	389	2	456[b]	284
AA	381	34[c]	2	913	139[c]
NA	437	32	1	9	41

[a] Insects were trapped each month from July to November 2000, data for each species analyzed for differences between additional summer aeration (SA + AA) versus autumn aeration only (AA)

[b] Fewer adults with additional summer aeration versus autumn aeration ($P < 0.05$, chi-square analysis).

[c] Fewer adults with autumn aeration only versus additional summer aeration ($P < 0.05$, chi-square analysis).

Table 5. Number of live lesser grain borers, red flour beetles, and rice weevils recovered after the summer aeration cycle in 2001-2002 from insect cage tubes placed at three positions, north (N), center (C), and south (S) positions.[a]

Location	Position	Bin	Lesser Grain Borer	Red Flour Beetle	Rice Weevil
N	0.08 m	SA + AA	280	20[b]	0
		AA	170[c]	65	0
		NA	180	55	0
	0.31 m	SA + AA	220[b]	75	17
		AA	450	84	2[c]
		NA	260	83	0
C	0.08 m	SA + AA	240	24[b]	0
		AA	225	72	0
		NA	240	80	0
	0.31 m	SA + AA	230[b]	82[b]	13
		AA	340	106	0[c]
		NA	230	63	0
S	0.08 m	SA + AA	250	48[b]	11
		AA	225	72	0
		NA	155	61	0
	0.31 m	SA + AA	185[b]	88	0
		AA	350	58[c]	0
		NA	170	86	0

[a] Two sets of cages of each species were put at each position (20 insects per cage) at depths of 0.08 and 0.31 m below the surface of the wheat in bins with summer aeration in addition to autumn aeration (SA + AA), autumn aeration only (AA), or no aeration (NA). Data summed for the two sets of cages, analyses made between bins SA + AA and AA.

[b] Significantly fewer live insects of each species, at each position and depth, in cage tubes from bin SA + AA compared to cage tubes from bin AA ($P < 0.05$, Chi-Square Analysis).

[c] Significantly fewer live insects of each species, within each position and depth, in cage tubes from bin AA compared to cage tubes from bin SA + AA ($P < 0.05$, Chi-Square Analysis).

Table 6. Number of live lesser grain borers, red flour beetles, and rice weevils recovered after the first autumn aeration cycle in 2001-2002 from insect cage tubes placed at three positions, north (N), center (C), and south (S) positions.[a]

Position	Bin	Lesser Grain Borer	Red Flour Beetle	Rice Weevil
0.08 m	SA + AA	0	1	4
	AA	0	2	21
	NA	0	3	65
0.31 m	SA + AA	0	0	5
	AA	0	0	9
	NA	0	6	45
0.08 m	SA + AA	59	58	3
	AA	60	58	39
	NA	60	59	29
0.31 m	SA + AA	59	58	0
	AA	60	60	20
	NA	60	60	92

[a] Two sets of cages of each species were put at each position (20 insects per cage) at depths of 0.08 and 0.31 m below the surface of the wheat in bins with summer aeration in addition to autumn aeration (SA + AA), autumn aeration only (AA), or no aeration (NA). Data summed for all three positions at each depth for each bin, no differences ($P > 0.05$, Chi-Square Analysis) in live insects between bins AA and SA + AA.

temperatures at 0.08 and 0.31 m in the bins during the summer months. At the conclusion of the early autumn aeration cycle, there were few live lesser grain borers and red flour beetles in the tubes, but live rice weevils were present (table 6). However, at the conclusion of the second aeration cycle, live insects of all three species were present, but there was no reproduction. In addition, there were no differences between positions for either aeration cycle (table 6).

Table 7. Total number of live rusty grain beetles, foreign grain beetles, hairy fungus beetles, red flour beetles, and lesser grain borers recovered from pitfall traps placed on the surface of wheat at the north, south, east, west, and center positions in bins aerated in summer plus standard autumn aeration (SA + AA), autumn aeration only (AA), or no aeration (NA). Insects were trapped each month from July to November 2000, data for each species analyzed for differences between additional summer aeration (SA + AA) versus autumn aeration only (AA).[a][b]

Month	Bin	Rusty Grain Beetle	Foreign Grain Beetle	Hairy Fungus Beetle	Red Flour Beetle	Lesser Grain Borer
July	SA + AA	15	13[a]	70[a]	1	0
	AA	17	183	725	1	5
	NA	22	108	103	2	5
Aug.	SA + AA	186[a]	33[a]	42[a]	90	1[a]
	AA	903	176	837	44[b]	104
	NA	500	197	77	72	44
Sept.	SA + AA	189[a]	74	99[a]	569	34[a]
	AA	1345	48[b]	905	148[b]	1236
	NA	595	91	99	335	560
Oct.	SA + AA	37[a]	165[a]	82[a]	275	0
	AA	266	269	366	55[b]	0
	NA	[c]	[c]	[c]	[c]	[c]
Nov.	SA + AA	29[a]	462	0	175	0
	AA	107	57[b]	12	35[b]	0
	NA	[c]	[c]	[c]	[c]	[c]

[a] Significantly fewer live insects of each species, at each position and depth, in cage tubes from bin SA + AA compared to cage tubes from bin AA ($P < 0.05$, Chi-Square Analysis).

[b] Significantly fewer live insects of each species, at each position and depth, in cage tubes from bin AA compared to cage tubes from bin SA + AA ($P < 0.05$, Chi-Square Analysis).

[c] The cones of the probe traps that were put in the unaerated bin were so heavily infested with red flour beetles and lesser grain borers that accurate counts could not be made. Numbers estimated by volumetric means were more than 10,000 lesser grain borers and red flour beetles total collected from the five probe traps.

Data from the probe traps showed mixed results with summer aeration (table 7). There were 19 comparisons in which there were significant differences between the bin with summer aeration and the bin with autumn aeration only (P < 0.05), and in 13 of these 19 instances there were fewer insects of the particular species in the bin with summer aeration. However, the primary difference was in the red flour beetle populations; and they were generally lower in the bin with autumn aeration only than in the bin with summer aeration. There were only two occasions where there was a significant difference in lesser grain borer populations (P < 0.05), and in both of these cases there were fewer lesser grain borers in the bin with summer aeration.

2002-2003

Mixed results were obtained from the cage tubes. At the north and center positions, there were fewer lesser grain borers after the first aeration cycle in the bin with autumn aeration only compared to the bin with summer aeration, the reverse was true for the south position (table 8). Red flour beetles and rice weevils did not develop inside the tubes, possibly because of the warmer temperatures. As in previous years, there was no population development of any species during the two autumn aeration cycles (table 9). There were mixed results in the counts from the probe traps, populations of rusty grain beetles and foreign grain beetles were generally lower in the bin with summer aeration than in the bin with autumn aeration only, the reverse was usually true for the red flour beetle (table 10). Lesser grain borer populations did not develop in the bins to the extent of the previous years.

Table 8. Number of live lesser grain borers, red flour beetles, and rice weevils recovered after the summer aeration cycle in 2002-2003 from insect cage tubes placed at three positions, north (N), center (C), and south (S) positions.[a]

Location	Position	Bin	Lesser Grain Borer	Red Flour Beetle	Rice Weevil
N	0.08 m	SA + AA	246	9[b]	0
		AA	132[c]	22	0
	0.31 m	SA + AA	312	25	0[b]
		AA	135[c]	25	12
C	0.08 m	SA + AA	184	1	0
		AA	156	8	0
	0.31 m	SA + AA	310	15	0
		AA	230[c]	10	0
S	0.08 m	SA + AA	204[b]	13	0
		AA	262	11	0
	0.31 m	SA + AA	122[b]	8	0
		AA	179	8	0

[a] Two sets of cages of each species were put at each position (20 insects per cage) at depths of 0.08 and 0.31 m below the surface of the wheat in bins with summer aeration in addition to autumn aeration (SA + AA) or autumn aeration only (AA). Data summed for the two sets of cages, analyses made between bins SA + AA and AA.
[b] Significantly fewer live insects of each species, at each position and depth, in cage tubes from bin SA + AA compared to cage tubes from bin AA (P < 0.05, Chi-Square Analysis).
[c] Significantly fewer live insects of each species, within each position and depth, in cage tubes from bin AA compared to cage tubes from bin SA + AA (P < 0.05, Chi-Square Analysis).

Table 9. Number of live lesser grain borers, red flour beetles, and rice weevils recovered from insect cage tubes placed at three positions, north (N), center (C), and south (S) positions.[a]

Position	Bin	Lesser Grain Borer	Red Flour Beetle	Rice Weevil
0.08 m	SA + AA	54	58	58
	AA	60	60	56
0.31 m	SA + AA	53	57	59
	AA	58	57	57
0.08 m	SA + AA	11	12	9[b]
	AA	9[c]	16[d]	15[e]
0.31 m	SA + AA	7	20[f]	13
	AA	7	9[g]	7

[a] Two sets of cages of each species were put at each position (20 insects per cage) at depths of 0.08 and 0.31 m below the surface of the wheat in bins with summer aeration in addition to autumn aeration (SA + AA) or autumn aeration only (AA). Data summed for all three positions at each depth for each bin, no differences (P > 0.05, Chi-Square Analysis) in live insects between bins AA and SA + AA.
[b] 1 from center position, 8 from south position.
[c] 6 from center position, 3 from south position.
[d] 2 from center position, 14 from south position.
[e] 3 from center position, 12 from south position.
[f] 1 from center position, 19 from south position.
[g] 1 from center position, 8 from south position.

Discussion

Results from model simulation studies had previously shown that summer aeration at 23.7°C would reduce overall temperatures inside the bulk wheat mass in a typical storage bin (Flinn et al., 1997). Results from this field study showed summer aeration could cool stored wheat, but the level of cooling was dependent on the time aeration was initiated and the ambient temperature profiles for that particular year.

Table 10. Total number of live rusty grain beetles, foreign grain beetles, hairy fungus beetles, red flour beetles, and lesser grain borers recovered in 2002-2003 from pitfall traps placed on the surface of wheat at the north, south, east, west, and center positions in bins aerated in summer plus standard autumn aeration (SA + AA) and autumn aeration only (AA).[a]

Month	Bin	Rusty Grain Beetle	Foreign Grain Beetle	Hairy Fungus Beetle	Red Flour Beetle	Lesser Grain Borer
July	SA + AA	33	37[b]	17	11	0
	AA	0[c]	65	7	4	0
Aug	SA + AA	214	43[b]	56[b]	388	1
	AA	218	152	105	76[c]	5
Oct.	SA + AA	179[c]	0	174	388[b]	20
	AA	228	0	194	574	17
Nov.	SA + AA	2	0	0	2	0
	AA	6	0	0	1	0
Dec.	SA + AA	56[b]	0	15	54[b]	9
	AA	109	0	15	126	3

[a] Insects were trapped each month from July to December 2002, except for November. Data for each species analyzed for differences between additional summer aeration (SA + AA) versus autumn aeration only (AA).
[b] Significantly fewer live insects of each species, at each position and depth, in cage tubes from bin SA + AA compared to cage tubes from bin AA (P < 0.05, Chi-Square Analysis).
[c] Significantly fewer live insects of each species, at each position and depth, in cage tubes from bin AA compared to cage tubes from bin SA + AA (P < 0.05, Chi-Square Analysis).

If wheat could be binned immediately after harvest, aeration could begin immediately so that more cooling hours below 23.7°C would be available for summer aeration. Even with our late starting date, summer aeration was effective, as shown in table 1 and by the temperature profiles at depths of 0.9 and 1.8 m.

During the summer, the temperature at the top surface of unaerated wheat stored in Kansas is not conducive to insect growth and development. The temperature at the surface of the bins without summer aeration was generally 35°C to 40°C, which is outside the optimal developmental range for most stored-product insects (Howe 1965; Fields, 1992), with the possible exception of the lesser grain borer. Populations of the rice weevil and red flour beetle were generally much lower in bins without summer aeration. In the bins without aeration, the elevated surface temperatures during the initial summer months of the study could have inhibited population growth, and summer aeration simply reduced temperatures on the upper grain surface to levels that were more favorable for development of these two species. Caged insects were subject to the environment in which they were placed, but in natural infestations they can enter the bin and encounter the grain surface, then disperse slowly downward from that point (Hagstrum 1987, 1989). Insects move and respond to temperature gradients (Flinn and Hagstrum, 1998), therefore if they encounter elevated temperatures on the surface, they could simply disperse downward into cooler areas. Aeration reduces temperature gradients inside the bulk grain mass and equalizes temperatures, which is what occurred in the bins with summer aeration. Summer aeration could be especially beneficial for control of the lesser grain borer. Although high temperatures are often a limiting factor in insect development, Cotton et al. (1960) documented reproduction and development of the lesser grain borer at 37°C, and field studies have shown high populations of lesser grain borer during the summer months in wheat stored in Kansas (Reed and Harner, 1998ab).

Stored-grain insects can quickly locate and infest stored grain, often within one to three weeks after binning (Hagstrum 1987, 1989; Reed et al., 1991; Dowdy, 1994; Dowdy and McGaughey, 1994; Hagstrum, 2001). Resident insect populations within storage facilities can also be important sources of infestation (Reed et al., 2003). Aeration will reduce but may not completely eliminate an existing infestation, as shown in a study conducted in the United Kingdom by Armitage and Stables (1984). Existing populations of the saw-toothed grain beetle, *Oryzaephilus surinamensis* (L.), the rusty grain beetle, and the granary weevil, *Sitophilus granarius* (L.), were reduced by aeration, but some live rusty grain beetles and granary weevils were still found after 20 months of storage. In a related study, populations of the saw-toothed grain beetles survived during the winter in bins that had been previously aerated (Armitage and Llewellin, 1987).

In the current study, there appeared to be some resident infestation of rusty grain beetles, hairy fungus beetles, and foreign grain beetles, because these species were present at the start of the storage season in all three years. They could have infested the wheat before it was brought to the commercial elevator, during the process of transfer to our facilities, or in the process of loading the three experimental bins. In each year, the experimental bins were thoroughly cleaned before the new crop wheat was loaded into the bins, so it does not seem that resident populations within the bins themselves caused the infestation. Regardless, summer aeration generally reduced the populations of those species compared to the bins with no summer aeration. The lesser grain borers that infested the bins in this study appeared to be from natural populations that detected the grain after it was binned, and summer aeration generally caused a population reduction compared to autumn aeration only. This species is a primary pest of stored wheat in the lower plains states, and is often detected in stored wheat during the summer months (Cuperus et al., 1986; Reed et al., 1991). The red flour beetles also appeared to be from natural populations, but mixed results were obtained with summer aeration. In contrast to the lesser grain borer, the red flour beetle tends to remain on the surface of the wheat, and it may simply be that aeration reduced the surface temperatures into a slightly more favorable range for this species, which was then reflected in the overall population.

Probe traps were used to assess insect populations in the wheat bins, and many studies have shown that probe traps are effective in estimating insect populations within a grain mass (White et al., 1991). However, there are a number of factors that can influence trap catch, such as temperature, insect density, insect species, and trapping duration (White and Loschiavo, 1986; Fargo et al., 1989; Reed et al., 1991). Probe traps provide a measure of relative but not absolute abundance (Hagstrum et al., 1999, although there are methods to relate the trap catch to absolute density (Hagstrum et al., 1998). The purpose of using probe traps in our study was to show how they could be used to evaluate the effectiveness of the various aeration treatments, and not to quantify insect populations.

The HOBO temperature recorders were an easy method to obtain recorded temperatures of the grain mass at various depths inside the bin. The sensors and cables were easy to install inside the grain mass, and it was simple to download temperatures from the sensors to the HOBO shuttle device, then transfer the data to a personal computer. Although this may be more labor-intensive than reading data from thermocouples, it does provide a means to accurately monitor the progression of an aeration cooling front through a grain mass. Many modern farming operations today utilize computers as part of their management systems, and the technology would be simple to adopt and utilize.

CONCLUSIONS

- Summer aeration produced cooling of 3.0°C to 3.8°C during July through early September compared to bins that were not cooled until autumn.
- Temperatures at the top surface of the grain were more favorable for insect development in the summer aerated bins than in those not aerated in summer.
- Natural insect populations were reduced in the summer aerated bins compared to bins not aerated during summer.
- Field data seem to support modeling simulation studies that predict lower insect populations when a summer aeration cycle is included, however, the timing and the effectiveness of this extra aeration may vary depending on when grain is stored, the weather patterns for a particular year, and the presence and severity of natural infestations of insects.

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