POTENTIAL AND LIMITATIONS OF THE USE OF LOW TEMPERATURES TO PREVENT INSECT DAMAGE IN STORED GRAIN

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INTRODUCTION: The full potential of the use of low temperatures to control stored-grain insects has not been realized, even in geographical locations where low temperatures are available and are relatively inexpensive to use in cooling grain sufficiently to inactivate or kill stored-grain insects and mites. We who live in temperate climates reap benefits of low ambient temperatures, even without putting forth any effort or expense, but we could economically increase the benefits by moving this cool air through our grain more than we do.

Discussion of the use of refrigeration to cool grain is discussed elsewhere in these Proceedings; refrigeration is being used to remove heat from grain in climates which do not provide naturally cool air, or in climates which have cool air only part of the year, as in temperate areas.

Both high and low temperatures have been used for a long time to kill insects, or at least reduce their damage, in grain and grain products. In the northern parts of the United States and in Canada, "freeze-outs" have been used to disinfest flour mills. The mills were opened for 24-48 hr when temperatures were very low, below -20°C (0°F). The effectiveness of this technique was demonstrated by Cotton and Frankenfeld (1) in Kansas; however, such severe temperatures cannot be depended on to occur in the state.

Dean (2) about 70 years ago demonstrated that flour mills in Kansas could be almost completely disinfested by "superheating" which created temperatures of 43-60 C°(110-140°F) in most of the mill. Although effective, this method was not used much. The sun's energy has been used directly to disinfest as well as to dry small lots of grain. Heating grain in fluidized beds is being studied, as reported by Dermott and Evans (3).

In the First Conference in 1974 in Savannah, Georgia, Nelson (4) and Kirkpatrick (5) presented papers on the use of different types of radiant energy to kill stored-grain insects by the heat produced as radiations were absorbed by the insects and/or the grain. At that same conference Navarro (6), Calderon (7), and Smith (8) dealt with various aspects of controlling stored-food insects using low temperatures.

Use of low temperatures is, and should be, of more interest these days because of insect resistance to insecticides, especially the protectant chemicals applied to grain as common practice in some places, and because of the increased concern, justified or not, that many people feel about having chemicals put on grain which they are going to eat in one form or another.

Any control method to be acceptable must meet certain requirements: it must be needed, it must be effective, it must be available, it must be economical, it must be amenable to safe application, and it must not harm the product or make it unsafe for humans or animals to consume. Malathion is a chemical that met these reqirements quite well and has been widely used directly on grain as a protectant, but its effectiveness has been decreasing due to resistance of the insects, more in some areas than in others.

Insecticides will continue to have their place in the protection of stored grain. This is evidenced by the continued search for and testing of new insecticides suitable for use on and around stored grain. Other potential control methods for protecting grain from pests should be investigated, and developed when and where appropriate. Thus, we see an active interest in various kinds of radiation, in pheromones, hormones, and pathogens, in varietal resistance, in various kinds of atmospheres, and in the use of temperatures detrimental to stored-grain pests.

Low temperatures are attractive because they do not harm the grain and because they retard the rate of deterioration due to respiration and microorganisms as well as that due to insects and mites. No potentially harmful residues result, and apparently no government agencies have yet required registration of low-temperature usage with all the problems that process involves.

SUSCEPTIBILITY OF INSECTS TO LOW TEMPERATURES: The optimum temperature for most stored-grain insects is between 25 and 39°C. Any lowering of the temperature below the optimum for a species will have some adverse effect. But to cool insects enough to prevent feeding and reproduction, the temperature must be lowered considerably: below 15-17°C for most species. Howe (9) summarized the estimates of optimum and minimum temperatures for population increases which had been reported by numerous investigators. He listed more than 50 species, some of which are given in Table I.

Burges and Burrell (10) listed 9 common grain-infesting species, giving the optimum temperature for development and the temperature at which the developmental cycle requires 100 days (Table II). They stated that, in general, if temperature is reduced to a level at which a species takes 100 days to develop, that species is unlikely to multiply to a dangerous extent.

If moisture content is sufficient for mites, lower temperature is required for protection of the grain. Smith (8) listed the minimum and optimum temperatures for development of some mite species common in stored products (Table III).

TABLE I. Estimated optimal and minimal temperatures (°C) for population increase for selected stored-grain insects. (Adapted from Howe, 1965).

Species	Min.	Opt.
Species Needing High Temp.		
Cold Hardy		
Trogoderma granarium Everts	24	33-37
Cryptolestes ferrugineus (Stephens)	23	32-35
Oryzaephilus surinamensis (L.)	21	31-34
Plodia interpunctella (Hubner)	18	28-32
Moderately Cold Hardy		
Tribolium confusum Jacq. duVal	21	30-33
Ephestia cautella (Walker)	17	28-32
Rhyzopertha dominica (Fab.)	23	32-35
Cold Susceptible		
Tribolium castaneum (Herbst)	22	32-35
Callosobruchus maculatus (Fab.)	22	30-35
Oryzaephilus mercator (Fauvel)	20	31-34
Cryptolestes pusillus (Schönherr)	22	28-33
Species Thriving at Moderate Temperature		
Cold Hardy		
Anagasta kuehniella (Zeller)	10	24-27
Sitotroga cerealella (Olivier)	16	26-30
Sitophilus granarius (L.)	15	26-30
Acarus siro L.	7	21-27
Moderately Cold Hardy		
Sitophilus oryzae (L.)	17	27-31
Cold Susceptible		
Gnatocerus cornutus (Fab.)	16	24-30

TABLE II. Optimum temperature (°C) and temperature at which developmental cycle requires 100 days. (Adapted from Burges & Burrell, 1964).

Species	Opt.	Temp. for 100-day devel. cycle
Oryzaephilus surinamensis (L.)	34	19
Sitophilus granarium (L.)	28-30	17
Cryptolestes ferrugineus (Steph.)	36	20
Tribolium castaneum (Herbst)	36	22
T. confusum Jacq. duVal	33	21
Trogoderma granarium Everts	38	22
Sitophilus oryzae (L.)	29-31	18
Rhyzopertha dominica (Fab.)	34	21
Cryptolestes pusillus (Schonherr)	32	19

TABLE III. Minimum temperatures (°C) for development of some stored-product mites (Smith, 1974).

Species	Min.
Acarus siro L.	0
Glycyphagus domesticus (DeGeer)	0-5
Tyrophagus putrescentiae (Schrank)	8
Cheletus eruditus (Schrank)	10

minimum temperature for development ranges from 0 to 10°C. Sinha (11) listed 10 species of storage mites of importance in Japan and summarized the minimum and optimum temperatures for breeding, as reported by several investigators (Table IV). The minimum temperature ranges from 7 to 15°C. Temperature just low enough to effectively retard insect development (17°C) will be quite suitable for buildup of certain mite populations.

Table IV. Estimates of minimum and optimum temps. (°C) at which 4 mites breed. (Adapted from Sinha, 1968).

Species	Min.	Opt.
Tyrophagus putrescentiae (Schrank)	9-10	23-28
Glycyphagus destructor (Schrank)	10,15	15-25
Acarus siro L.	7	23-30
Cheletus eruditus (Schrank)	12	25-27

Solomon and Adamson (12) exposed numerous species of stored-product insects to winter conditions in various situations in Britain, and ranked them in categories from "very susceptible" to "hardy."

Knowledge of the species involved and of their relative susceptibilities to low temperatures permits more effective use of low temperatures where they are available. In geographical areas where ambient temperatures are marginal for cooling by aeration, they may be effective if the only insect pests are relatively susceptible to low temperatures.

ACCLIMATION OF INSECTS TO LOW TEMPERATURES: is known that some insects (perhaps all of them) acclimate if exposed to gradually decreasing temperatures, and thus are able to survive longer cold exposure and/or lower temperatures than those not acclimated.

Smith (13) found that survival of *Cryptolestes ferrugineus* (Stephens) adults acclimated for 7 or more days at 15°C and then exposed to -6°C was much greater than for those not acclimated. And whereas nonacclimated adults did not survive 3 days at -12°C (10°F), survival was 40.5% of those acclimated for 14 days at 15°C then exposed for 14 days at -12°C. For those acclimated for 28 days at 15°C, survival was 60.8% after 78 days at -12°C (Table V).

TABLE V. Percentage survival of *Cryptolestes ferrugineus* exposed to -12°C after acclimation at 15°C. (From Smith, 1970).

Days of acclimation	Survival
None	0 after 3 days
14	40.5% after 14 days
28	60.8% after 78 days

The supercooling point was -16.7°C for nonacclimated insects, but was -20.4°C after 3 or 4 weeks of acclimation. Smith suggested that this species is able to survive in unheated granaries in the Prairie Provinces of Canada because of its ability to acclimate to low temperatures.

Insects that can move through the grain mass are not exposed to sudden temperature changes and so are able to acclimate according to their capacity to do so.

Evans (14) found that the mean chill-coma temperature (ET_{50}) of *Sitophilus oryzae* (L.) was lowered from 8.43°C for unacclimated adults to 5.29°C for adults acclimated for 8 weeks at 15°C. Mean chill coma of *S. granarius* (L.) treated the same way was lowered from 5.26 to 2.71°C.

Ernst and Mutchmor (15) demonstrated that adults and larvae of *Tenebrio molitor* Fab., *Tribolium confusum* Jacq. duVal, and *Trogoderma variabile* Ballion dispersed more at low temperatures after acclimation at 15 or 23°C than did insects acclimated at higher temperatures.

Sinha (16) reported that 1% of an *Acarus siro* L. culture reared at 6°C for 2 years survived -18°C for 168 hr, while none of a culture reared at 21°C for 1 year survived 72 hr exposure at -18°C.

David et al. (17) acclimated various developmental stages of *Sitophilus oryzae*, *S. granarius*, and *Rhyzopertha dominica* (Fab.) for 3 days at 21°C, for 7 days at 15.5°C, and for 7 days at 10°C, then exposed them to 4.4°C for 2, 4, or 6 weeks. Acclimation increased survival of all species. Although a laboratory strain and a field strain of each species were tested, there was little difference in response, except that field-strain *S. granarius* adults were more cold hardy than the laboratory-strain adults. The hardiest immatures of *S. oryzae* were those of 14-17 days' development, and, when acclimated, more than 25% survived 6 weeks at 4.4°C, while none of the nonacclimated survived (Table VI. Of acclimated *S. granarius* of the same developmental age, 75% or more survived the same exposure while few of the nonacclimated survived. The immatures of *R. dominica* with 21-24 days' development were the most cold hardy but were more susceptible than the other two species. Virtually none, acclimated or not, survived 6 weeks at 4.4°C, and only 9-18% of the acclimated group survived 4 weeks; none of the nonacclimated survived 4 weeks. Only a few acclimated *S. oryzae* adults survived 2 weeks' exposure to 4.4°C, and almost none of the nonacclimated ones survived. Thirty-nine percent of *R. dominica* adults survived 2 weeks' exposure to 4.4°C and only 6-8% survived 4 weeks, while only 1-2% of nonacclimated adults survived 2 weeks. *S. granarius* adults were much more cold hardy, with 90% of the acclimated field-strain adults surviving 6 weeks compared to less than 2% of nonacclimated field-strain adults. Field-strain adults were clearly more cold hardy, whether acclimated or not.

Granovsky and Mills (18) exposed *S. granarius* adults in pint jars (250 insects/250 g wheat) to temperatures gradually decreasing from 26°C to 4.4°C over a period of 109 days. Temperature was decreased in increments of 2.2 C°or less per week. The insects were held at 4.4°C for 9 days, then 100 of them were each placed individually with an undamaged wheat kernel and 100 individually with a kernel with about one-third of the "brush" end cut off. They were held at 4.4°C for 15 days, then at 5.5, 6.5, and 8.0°C for 18, 10, and 7 days, respectively. There was evidence of feeding at all temperatures, but only on cut kernels; the insects apparently were unable to penetrate the pericarp of the kernels at those temperatures. Of 100 weevils in each group, 24 survived on cut kernels to the 161st day of the temperature sequence (after 50 days' isolation with single kernels), while only 10 survived on sound kernels. Although nonacclimated adults were not used as controls to determine degree of acclimation, the tests showed that *S. granarius* can feed on damaged kernels at quite low

TABLE VI. Percent survival (of control) at 4.4°C of acclimated and non-acclimated insects at different developmental stages. (Adapted from David et al., 1977).

Weeks expos. 4.4°C	Acclimated		Non-acclimated	
	Lab.	Field	Lab.	Field
S. oryzae of 14-17 days development				
2	82.8	83.8	1.2	1.6
4	48.4	53.1	0.0	0.0
6	36.6	26.1	0.0	0.0
S. granarius of 14-17 days development				
2	97.1	81.8	36.6	38.1
4	75.8	54.3	2.6	4.1
6	82.8	74.5	0.1	0.9
R. dominica of 21-24 days development				
2	76.9	55.6	16.4	16.0
4	18.3	9.2	0.0	0.0
6	0.3	0.0	0.0	0.0
S. granarius adults				
2	85.8	100.1	33.7	92.7
4	25.9	90.8	3.9	78.3
6	15.7	90.1	0.0	1.8

temperatures and that the proportion surviving is thus increased.

Granovsky (19) found that, during acclimation, *S. granarius* gained dry weight, total lipids, and triglycerides, and decreased in water content, while the opposite occurred for *T. castaneum*. This demonstrates the variability among species in adjusting to low temperatures.

Evans in two papers (20, 21) reported on the capacities for increase of several Australian populations of *S. oryzae* and *S. granarius* at 15°C. The finite rate of increase of *S. granarius* averaged 1.07/female/week, and of *S. oryzae* averaged 1.09/female/week. Evans found that capacity for increase of a given population at 15°C was correlated with fertility at an optimum temperature of 27°C and with body weight, rather than with cold tolerance (chill-coma temperature), or its previous temperature history. He found significant differences in capacity for increase among the populations. Temperature of rearing of immatures influenced capacity for increase at 15°C; weevils of laboratory populations reared at 27°C had a greater capacity for increase at 15°C than those reared at 15°C.

These and other studies not cited emphasize the survival value of acclimation for many of these insects, and also that some may be able to feed and reproduce at lower temperatures than commonly thought; Evans' papers reported that reproductive capacity can be affected by the temperature history of the immatures.

Until more is known about the effects of various kinds of exposures to low temperatures on insects, we will not be capable of recommending precise temperatures for their control. Obviously, we need not wait for all desired information before using low temperatures to control insects; the method is being used successfully in a number of situations.

AVAILABILITY OF LOW TEMPERATURES: Low temperatures may be available naturally, or they may be created by refrigeration equipment (to be discussed in another paper).

In the United States from north to south we have a wide range of ambient temperatures. In Table VII are presented the contrasts in temperature at Fargo, North Dakota (47°N. Lat.); Wichita, Kansas (38°N. Lat.); and Brownsville, Texas (26°N. Lat., the Gulf of Mexico). Locations are shown in Figure 1. Weather records show that Fargo during the two warmest months (July and August) about 50% of the recorded hourly temperatures during 1951-1960 were under 21°C (70°F) and 12-16% below 15.5°C (60°F). In Wichita 10-12% of the observations were of temperatures below 21°C and only 0.5% below 15.5°C. At Brownsville the temperature was almost never below 21°C in July.

The temperatures observed during January, one of the coolest months, were all below 10°C (50°F) at Fargo, and 32% were below -18°C (0°F), as compared to only 14% below 10°C at Brownsville.

TABLE VII. Percentages of observed temperatures[a] below selected levels at different locations in U.S.A.

Location & Lat.		<21°C	<15.5°C	<10°C	<-18°C
July					
Fargo, N. D.	47°N.	45	12		
Wichita, Kans.	38°N.	12	0.5		
Brownsville, Tex.	26°N.	0.0			
August					
Fargo		52	16		
Wichita		10	0.5		
Brownsville		0.08			
January					
Fargo				100	32
Wichita				92	0.4
Brownsville				14	0.0

[a] Total of approx. 7400 hourly observations for each location during 1951-1960.

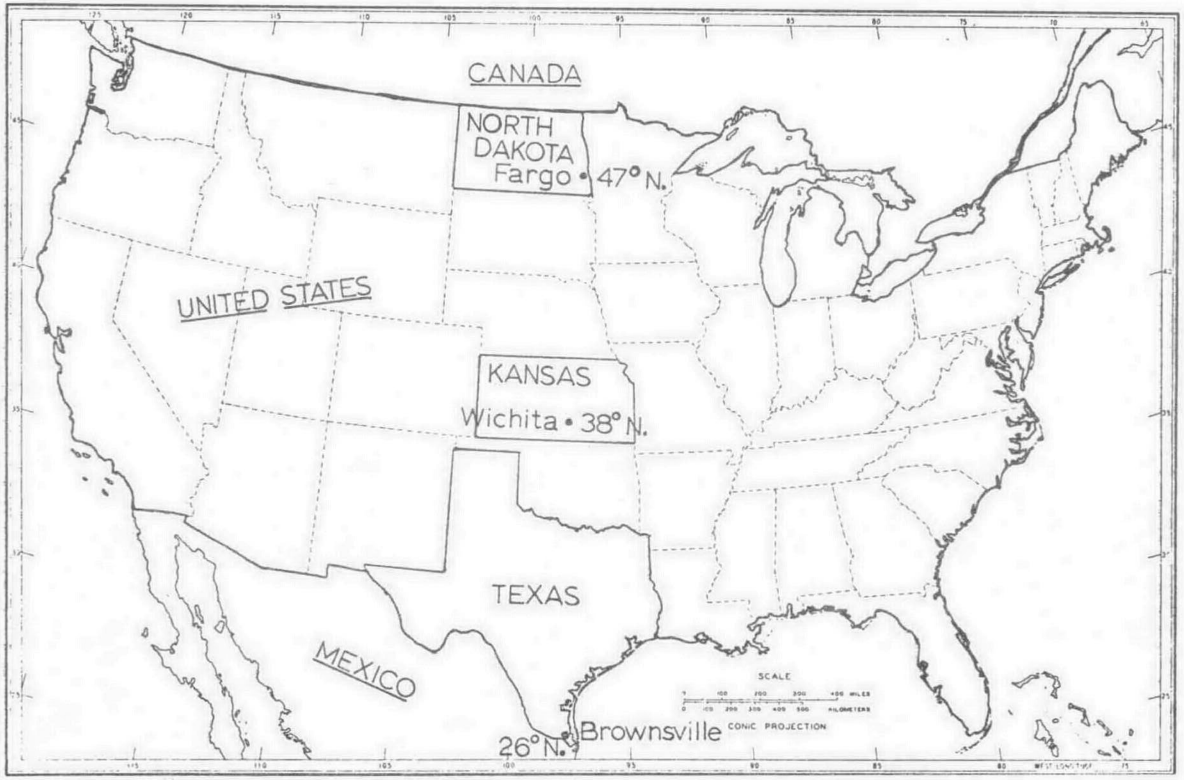

FIGURE 1. Latitude of 3 locations in the United States of America.

Aeration may be advantageous in areas where temperatures are not low enough to halt insect development. It equalizes temperatures throughout the store and by use of selective aeration, temperatures can be reduced below the optimum for insects, thus retarding population development. Aeration is being utilized in the warmer areas of Australia.

In Kansas, harvest of wheat begins just before July 1. The temperature of the grain at harvest varies greatly, but not uncommonly grain is at 30°C or higher when placed in storage. Although we do not have sufficiently low temperatures in July to cool grain below a "safe" temperature, it is recommended to farmers that they aerate grain immediately to remove the "field heat." The mean temperature for July may vary from 21 to 33°C, but over almost 100 years has averaged 27°C. Therefore, on the average, the temperature of grain can be reduced at least to 27°C by using aeration, and with selective aeration more than that. At Wichita, Kansas, in September (2 months after harvest) 43% of the observed temperatures were found to be below 21°C, and 14% below 15.5°C, so grain can be cooled to near the safe level, taking 15-17°C to be the safe level. In October, the temperature can be lowered effectively, since 50% of the hourly observed temperatures were found to be below 15.5°C.

It has been estimated that not more than 30% of the farmers in Kansas use aeration; many do not have the equipment, and those who do, do not use it as much as they should. We could make better use of it earlier in the fall. Benefits can be gained from aeration of grain even when temperatures cannot be lowered as much as desired.

Calderon (7), at the First Conference, discussed the potential for using aeration for controlling insects in warm climates. He pointed out the need for detailed weather data at the storage site so that it can be decided whether effective cooling can be done using ambient air. Also at that conference Navarro (6) discussed the use of aeration of grain as a means of controlling grain storage insects. Navarro et al. (22) reported observations on nearly 2 years' storage of 1142 tons of wheat in Israel, using only ambient aeration to cool the grain, a demonstration of practical use of aeration for cooling grain in a subtropical area.

Aeration is important not only to cool grain but also to equalize the temperatures throughout the grain mass to prevent moisture migration; furthermore, it may be used for ambient-air drying, particularly with high airflows.

Besides the papers already mentioned, there are others with good discussions of aeration of grain, such as Calderon's paper (23) presented at the Grain Storage Seminar in Ibadan in 1971; Burrell's chapter in the book edited by Christensen (24), Storage of Cereal Grains and Their Products (Burrell also has a chapter in that book on chilling); and a U.S. Department of Agriculture report by Holman (25).

Use of low temperatures, as with any control measure, must be economically feasible. Remarks here will be limited to use of ambient air. Costs range from nothing upward; in areas such as Fargo, North Dakota, small storages of grain may cool sufficiently and quickly enough without aeration, while larger storages may be cooled quickly with aeration. Each situation must be analyzed with regard to availability of suitable air, availability of aeration equipment, and costs of that equipment and of the increasing cost of energy to operate it.

COSTS OF COOLING BY AERATION--AN EXAMPLE: An example of relative costs of aeration and the use of chemicals in Kansas follows. The costs are only estimates, and labor cost is not taken into consideration. Per bushel or per ton costs for materials and labor vary with the size and type of storage facility.

Cost of protectant chemicals applied directly to grain:

Malathion	0.2¢/bushel
Pyrethrins - piperonyl butoxide	0.86¢

Cost of fumigants:

"80:20" ($CCl_4:CS_2$)	0.8¢/bushel
Phosphine	0.23¢
Methyl bromide	0.3¢

Estimated cost of aeration of a 3000-bushel bin of wheat:

Installation, including full, perforated floor:

Perforated floor	$1,000.00
Fan (1.5 hp)	500.00
	$1,500.00 = 50¢/ bushel capacity

Installation, including "Y" perforated duct, rather than a perforated floor:

Perforated duct	$ 200.00
Fan	500.00
	$ 700.00

Estimated life of fan is 15 years, so cost of equipment ranges from 1.5 to 3.3¢/ bushel/ year.

Cost of operation of the fan: Using 0.1 ft^3/min/bushel airflow, it takes approximately 120 hr for the cooling front to move through a mass of grain. The 1.5-hp motor consumes about 1.5 kilowatt-hr of electricity at a cost of about 5¢/kilowatt-hr, thus about 7.5¢/hr. For each aeration of 120 hr, the cost will be about $9.00, which equals 0.3¢/bushel.

For Kansas, one recommendation is for at least five aerations per year for wheat stored on the farm, with the first immediately after harvest to remove "field heat"; another perhaps 6 weeks later while temperatures are still too warm to effectively control insects. A month later, temperatures will usually be low enough that grain can be cooled to below the "safe" level as far as insects are concerned.

If five aerations are done, the total cost/year for wheat will be approximately 2-5¢/bushel. In areas farther north, costs will be considerably less. Also, important benefits other than insect control are gained by aeration. It prevents moisture migration, which is not prevented by use of chemicals, except that caused by insect-induced heating. Although the cost is greater than a single treatment with chemicals, the benefits exceed those of insect control alone, and with careful monitoring and selective aeration, total fan operation can be reduced.

FACTORS INFLUENCING EFFECTIVENESS OF COOLING USING AERATION: Several factors influence effectiveness of forced air cooling in controlling insects.

Condition of the grain mass. Sampling and monitoring of the grain should determine as accurately as possible the temperature, moisture content, extent of biological activity and the organisms causing it, and the variability in density and particle size in the grain mass (broken kernels, dust, chaff, etc.), which influence uniformity of airflow. A hot spot caused by molds or insects may not be cooled adequately.

Air-moving equipment. Design of the duct system in relation to the type of storage structure is important, as well as quality and power of the blower. The objective is an adequate and as uniform airflow as possible, in order to effectively and economically cool all parts of the grain.

Weather conditions. Familiarity with the temperature and humidity characteristics of the area, particularly where adequacy of low temperatures is marginal, will permit the most effective use of the low temperatures that are available.

Interrelationships of temperature, relative humidity, and moisture content. Understanding of the interrelationships of temperature, relative humidity, and moisture content is important, especially to prevent adding excessive moisture to the grain during aeration.

There is no doubt that low temperatures could be used to advantage more than they now are, at least in the United States--

particularly ambient aeration. All situations differ--climatic conditions, equipment and energy availability, expertise, the variable biological and physical factors within each grain store--and, of course, economic feasibility.

Use of low temperatures should be considered wherever feasible, either alone or in conjunction with other control methods; and more information should be accumulated on the effects of low temperatures on the biology, behavior, and ecology of the various grain insects.

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