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David W. Hagstrum
USDA-ARS

Paul W. Flinn
USDA-ARS

Carl R. Reed
Kansas State University

Thomas W. Phillips
Oklahoma State University

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12

Stored-grain Insect Areawide Pest Management

DAVID W. HAGSTRUM,¹ PAUL W. FLINN,²
CARL R. REED³ AND THOMAS W. PHILLIPS⁴

¹USDA-ARS Grain Marketing and Production Research Center, Manhattan, Kansas, USA (retired)

²USDA-ARS Grain Marketing and Production Research Center, Manhattan, Kansas, USA

³Department of Grain Science and Industry, Kansas State University, Kansas, USA

⁴Department of Entomology and Plant Pathology, Oklahoma State University, Stillwater, Oklahoma, USA

Introduction

Over 67 million t of wheat (2.5 billion bushels) are moved by truck, railcar or barge through the grain marketing system in the USA during a year (Hagstrum and Heid, 1988; <http://www.ers.usda.gov/Data/Wheat/YBtable04.asp>). In the USA, commercial grain storage facilities are called elevators (Reed, 2006).

Typically, wheat is transported from the farm first to the country elevators, then to terminal elevators and finally to mill or export elevators. Elevators received their name from the bucket elevator that conveys the grain to the top of the building, from where it can be distributed to different bins. Country (local) elevators tend to receive grain from a smaller geographical area and generally have less grain storage and handling capacity than do terminal elevators. Because the terminal, mill and export elevators receive grain from large geographical areas, stored-grain insect pests are managed most effectively by areawide pest management (AWPM) practices that target local infestations before insects are transported with the grain to larger elevators (Flinn *et al.*, 2003a, b, 2007a).

Wheat is harvested in the USA from June in the southern part of the wheat-growing region until August in the northern part (Hagstrum and Heid, 1988). Grain temperature, grain moisture and storage time are the main factors determining the risk of economic losses from insect infestation. Wheat harvested in June in southern regions is generally at higher risk because grain temperature is suitable for insect movement and reproduction for a longer time than is wheat harvested in August in northern regions. Currently, management of insect pests in the wheat marketing system is usually sufficiently effective to slow insect population growth and

prevent insect populations from increasing exponentially. During the 1977 and 1978 storage seasons in the USA, the average insect pest population in the wheat marketing system increased from 0.15 insects/kg (four insects per bushel) in June to 0.44 insects/kg (12 insects per bushel) in October, and then decreased as grain cooled in autumn and winter (Hagstrum and Heid, 1988).

The profits and losses from merchandizing grain are greater and more apparent to managers of grain businesses than the costs and losses from insect pests in the elevator. Perhaps, for the same reason, grain merchandizing is generally given the highest priority and the greatest attention, and pest management and other aspects of grain management receive less attention. Any advanced insect pest management programme that is introduced into this corporate culture must be cost-effective, minimize the risk of insect problems and require minimal attention.

Elevator Operation

The operating practices of elevators need to be considered when developing an AWPM programme. At elevators, grain is sampled, weighed and stored. Often, it also is dried, segregated, blended, aerated and/or fumigated. The bucket elevator moves the grain from the dump pit below ground level to the top of the building or elevator leg. At small elevators, a distributor directs grain to the storage bins. At larger elevators, belt, drag or screw conveyors must move the grain laterally from bucket elevator to the storage bins. Most elevators have more than one dump pit and bucket elevator. Bins in most elevator buildings are unloaded through a discharge spout at the bottom of each bin on to a reclaim conveyor that transports it laterally to the bucket elevator. The distributor, located just beneath the top of the bucket elevator, directs the grain to another storage bin, a lateral conveyor, a weighing bin or a load-out bin. Load-out bins are small bins located over the truck dump. Storage bins not located in the elevator building may have an overhead load-out spout on the external wall for unloading.

Elevators often store several different types of grain. Grain of the same type usually is segregated by moisture content, protein content or test weight (bulk density). To facilitate this segregation, elevators frequently have many bins, often of different capacities (see Table 12.1). Terminal elevators may have over 100 bins (Elevators 9, 11 and 12) and some large terminal elevators 1000 or more. Records related to grain quality typically are kept on a large diagram of the elevator's bin layout, referred to as a bin board. Information including grain quality characteristics, volume of grain in the bin and fill and fumigation dates is recorded on this bin board. Fumigation is the treatment of grain by a toxic gas, usually phosphine, to kill insect pests (Hagstrum *et al.*, 1999).

Often, grain from several bins is blended to consistently meet grain quality requirements or to upgrade grain quality. Grain from one to ten bins (see Table 12.2) is often blended together by metering grain from each bin on to a reclaim conveyor. Generally, grain from fewer bins is blended at country elevators than at terminal elevators.

Table 12.1. Numbers of concrete bins of different storage capacities at 12 elevators in Kansas.

Elevator	Storage capacity (thousands of bushels) per bin								Total	Total capacity at elevator (bushels)
	1–2	2–5	5–10	10–20	20–30	30–40	40–50	69		
1	1	6	3	4	8	0	0	0	22	264,158
2	1	3	0	8	3	0	2	0	17	277,404
3	5	12	2	6	0	0	0	2	27	323,432
4	3	17	1	20	0	0	0	0	41	401,459
5	1	19	6	0	14	0	0	0	40	517,708
6	1	1	10	5	1	0	8	0	26	539,986
7	1	6	18	1	22	0	1	0	49	815,086
8	1	8	21	0	2	7	12	0	51	976,092
9	12	12	54	6	48	0	0	0	132	1,646,774
10	1	5	18	8	29	0	17	0	78	1,801,929
11	2	42	42	29	34	6	0	0	155	2,075,390
12	0	9	42	12	4	22	44	0	133	3,035,777
Total	29	140	217	99	165	35	84	2		

Table 12.2. Number of bins used to make wheat blends at Kansas elevators.

Number of bins	Internal movement				Outbound movement	
	Terminal elevator		Country elevator		All elevators	
	Frequency	% of total	Frequency	% of total	Frequency	% of total
1	63	26.8	94	78.3	9	11.7
2	51	21.7	19	15.8	17	22.1
3	50	21.3	2	1.7	16	20.8
4	36	15.3	5	4.2	11	14.3
5	24	10.2			10	13.0
6	6	2.6			3	3.9
7	4	1.7			2	2.6
8	0				4	5.2
9	1	0.4			1	1.3
10					4	5.2
Total	235		120		77	

Economic Losses Attributed to Insects

Insects are objectionable by their mere presence in a food commodity, but also produce kernel damages, and may leave webbing or an undesirable odour in the grain. In the grain industry in the USA, wheat millers are very sensitive to the kernel damage caused by the internal-feeding insect species, i.e. the lesser grain borer, *Rhyzopertha dominica*, and the rice weevil, *Sitophilus oryzae*. The larvae of these species develop within individual kernels, consuming grain material and leaving cast exoskeletons and other insect filth inside a kernel of grain. When the adult emerges from a kernel of wheat, a distinctive orifice is formed. Kernels with this injury are called insect-damaged kernels (IDK) by industry and regulatory personnel. Each adult insect is associated with one IDK, and the density of IDK increases over time if the insect population is not suppressed. Even if the insects are killed by fumigation, the IDK levels remain the same.

Internally infested kernels lead to insect filth in the flour made from the wheat. Microscopic fragments of insect exoskeletons in flour are considered animal filth, and are limited by a bakers' contract specifications and by government regulators. To minimize the insect filth in the flour and to ensure that the miller can mill flour with fewer than 15 insect fragments per 50 g, flour millers limit the density of IDK in wheat through contract specifications and receiving norms. Typical limits are very strict, often five or fewer IDK per 100 g of grain, or about 0.14% or less by weight. The regulator's (Food and Drug Administration – FDA) actionable limit is 75 fragments per 50 g of flour. Similarly, the official grain-grading agency (Federal Grain Inspection Service (FGIS) of the Grain Inspection, Packers and Stockyards Administration – GIPSA) may condemn wheat containing more than 32 IDK per 100 g as

being unfit for human consumption, and allowing it to be used only for animal feed or non-food industrial uses.

Insect-related costs in grain elevator operations in the USA are of two types (Hagstrum *et al.*, 1999). The first is penalties levied for insect presence and/or insect damage in grain by the purchaser or receiver. The second is the cost of managing insects to prevent the price penalties. In many cases, the cost of managing insects may be much larger than the cost of damage or penalties.

Penalties often take the form of a price discount, i.e. a lower price per unit of grain when grain containing live insects or insect-damaged kernels is received. Less apparent, but just as real, are the additional costs of locating an alternative market and of transporting the grain to that market when a shipment of grain is rejected for insect-related reasons at a destination. In many cases the costs are not apparent, such as when grain cannot be shipped to the preferred, higher-price market because of insect presence or damage, or when a supplier is quoted a lower price than a competitor because of his reputation for infested and/or damaged grain. Researchers have no way of quantifying several of these types of penalties or of separating the insect-related penalties from penalties related to other grain quality factors. For example, wheat that is desirable for its high bulk density and protein content would be less likely to be refused or discounted if an insect were found in the sample than would grain of lower quality in which the same type of insect was found. Similarly, it is difficult to quantify the value of the storage space occupied by insect-damaged grain as it waits to be blended into better-quality grain. In many cases, this space otherwise would generate storage revenue.

At the 'farm-gate' end of the grain marketing system, such as when the farmer delivers wheat to a country or terminal elevator, or a flour mill, or when wheat moves from country to terminal elevators, samples are taken and examined before the grain is accepted. Each receiver has acceptance criteria and discount scales for various quality factors, including the presence of live adult insects and the kernel damages caused by the insects. Nearer to the final consumer, the receiver is more likely to accept the official inspection certificate instead of investing in sampling and grading. A competent shipper may be able to avoid the price discounts while shipping large quantities of damaged grain by keeping the level of damage from affecting the grade. Thus, the costs to the shipper of the insect-related damage may be only those related to the cost of holding and blending the damaged grain. This common practice is the mechanism by which the grain trade in the USA deals with most IDK.

The cost of insect-control practices is similarly difficult to separate from the costs of activities that would be performed even if insects were not present. Where wheat is harvested wet, it must be dried and cooled to prevent damage by moulds. It must be transported to storage facilities and blended whether insects are present or not. Thus, the portion of the cost for these activities that should be assigned to insect pest management is arbitrary. Where wheat is stored in bins without aeration capability, it is turned – moved from one bin to another – to cool it. The fumigation is accomplished during the turn, but the cost of the fumigant is minor compared with the costs of electricity, manpower, capital depreciation and grain shrink (loss in volume of grain resulting from handling).

The grain sampling rates of 0.5 kg of wheat per 2000 to 3000 bushels used in the USA are adequate for characterizing the grain quality, but they are too low to

provide much sensitivity to insect presence. This low sampling rate sometimes results in large numbers of insects being transported in the grain without detection. A case study by the authors at the Kansas terminal elevator illustrates the commercial impact of different sampling rates and methods. Researchers sampled for insects in wheat outbound to a 100-car train by taking a total of 31.7 kg of grain per railcar. The average insect density observed was 2.1 insects/kg. At the same time, official grain inspectors examined 1 kg of sample per railcar, using samples collected by automatic diverter samplers. They found sufficient insects to declare that 14 of the 100 railcars contained infested wheat. The shipper called for a re-inspection, which was performed by manually probing the grain surface in each suspect railcar. Based on this second examination, all lots that had been graded 'infested' were deemed to be 'not infested', so certificates without the 'infested' designation were issued. If the grain contained the same insect density when it came to rest in the railcars as it had in the elevator basement where the researchers' samples were collected, nearly 19 million insects were shipped in that unit train without a single grade certificate indicating the presence of insects. Some grain receivers rely on the grading certificate only in making their purchase, and would not have been advised of the insect presence.

Insect Population Trends

Since the grain-handling industry began adopting phosphine fumigation more than 50 years ago, managers in the US grain-handling firms generally have not looked to science to provide solutions to their insect pest management problems. This may in part be because previous scientific studies did not provide the information needed to improve pest management. Financial support from government and industry has been sufficient to establish research programmes on stored-product insect problems at only a few land-grant universities. Recently, researchers have provided information on insect populations at typical grain elevators in the USA that can improve pest management.

Sampling with a vacuum probe at elevators in Kansas and Oklahoma has shown that insect populations increased from June to October, then levelled off and declined as autumn and winter temperatures cooled the grain (see Fig. 12.1).

The primary insect pests of stored wheat are *Cryptolestes ferrugineus* (the rusty grain beetle), *R. dominica*, *S. oryzae*, *Tribolium castaneum*, (the red flour beetle) and the sawtoothed grain beetle, *Oryzaephilus surinamensis*. A computer simulation model correctly predicted that, with an immigration rate of 0.35 *R. dominica* per ton of wheat per day, *R. dominica* would increase from 0.1 to 3.5 insects per kg of wheat from 20 September to 14 December (see Fig. 12.2). Populations decreased in March, April and May primarily due to low grain temperatures. The immigration rate for a new model for elevators was 50% higher than that for the old model predicting insect population growth on farms. The immigration rates at these elevators were probably higher than normal and rates that are ten- or 100-fold lower are probably common.

Insects generally do not infest wheat in the field in Kansas or Oklahoma. However, some infested grain that has been stored on farms may be delivered to elevators along with newly harvested grain. In Kansas, probe trap catches indicate that insects present at elevators infest grain soon after it is stored in bins (Reed *et al.*, 2001). Insects first infest grain at the surface, and insect densities decrease with the depth

Fig. 12.1. Seasonal trends for average number of insects/kg sample of wheat for grain stored at elevators in Kansas and Oklahoma.

Fig. 12.2. Growth rate of *R. dominica* in Kansas and predictions of computer simulation models (from Flinn *et al.*, 2004).

below the grain surface (see Fig. 12.3). *R. dominica* tended to move down during the grain storage period. This depth distribution pattern may be altered when grain is moved or when the grain from two or more bins is blended.

If the depth distribution of the insect populations is known, the insect density in the grain can be estimated at any point in the bin discharge. Wheat in discharge spouts has been shown frequently to contain a higher insect density than the bulk of

Fig. 12.3. Depth distribution of two species of insect pests in concrete bins at elevators in Kansas.

the grain, so the first grain discharged is likely to have a high insect count. If the grain surface is more densely infested than the rest of the mass, the point in the discharge when the majority of the insects are loaded out depends on whether the grain flow is of the funnel-flow, mass-flow or transitional type. The bin dimensions and geometry (Reed, 2006) influence this flow pattern.

In tall bins, mass flow, with every kernel moving towards the discharge spout at the same velocity, occurs until the distance between the grain surface and bin floor is 1.5 to 3.5 times the bin diameter. The grain near the bottom is discharged first. The flow pattern converts to funnel flow when the distance between the grain surface and bin floor is 1.5 to 3.5 times the bin diameter, and then only the grain directly above the discharge spout and a thin layer from the grain surface are in motion.

The species composition of insects in grain at elevators in Kansas was studied by taking several types of grain samples. Discharge spout (DS) samples were taken by opening the slide gate at the bottom of the bin and allowing about 10 kg of grain to fall on the stationary belt. A 3.9 l (3 kg) sample was taken from this grain. When a pile of residual grain was found outside bins or in an empty bin, a 3.9 l sample was collected. If the pile was smaller than 3.9 l, the entire pile was taken as a sample of grain residue. Grain samples of 3.9 l were collected with a vacuum probe as the probe was pushed through a 1.2 m layer of grain. For truck samples, 3.9 l of grain were removed from the grain stream as the grain was dumped from the truck.

The species composition in grain residues was found to be quite different from that in the wheat stored in bins (see Table 12.3). *R. dominica* density was low in grain

Table 12.3. Species composition of insect pests in various types of grain samples from Kansas elevators (from Reed *et al.*, 2003; Arthur *et al.*, 2006).

Type of sample, location or time grain sampled ^a	Percentage of each insect pest species				
	<i>R. dominica</i>	<i>S. oryzae</i>	<i>C. ferrugineus</i>	<i>T. castaneum</i>	<i>O. surinamensis</i>
DS samples after 89 days, bins not cleaned	1.1	47.8	14.6	35.0	1.5
Residual grain outwith bins	1.4	46.7	36.7	13.8	1.3
Maize residues from empty bins	2.1	25.2	55.3	17.4	0.1
DS samples after 49 days, bins not cleaned	5.0	50.4	8.7	35.6	0.3
DS samples January–June	8.1	4.5	78.7	1.1	7.7
Grain residues from empty bins	9.0	32.4	45.0	10.6	3.0
DS samples June–December	9.3	14.3	53.9	15.6	6.7
Residual wheat from empty bins	14.0	32.1	40.7	8.2	5.0
DS samples after 89 days, clean bins	19.1	32.7	32.7	4.4	11.1
DS samples after 49 days, clean bins	22.6	60.3	14.4	2.1	0
Vacuum probe samples January–June	29.3	5.7	38.6	18.7	7.7
Vacuum probe samples June–December	35.3	7.9	38.7	6.3	11.3
Vacuum probe samples 0–3.7 m depth	44.2	1.0	35.7	19.0	0.1
Truck samples for grain from elevators	46.0	7.3	23.1	19.8	3.8
Truck samples for grain from farms	52.4	0.4	8.8	36.0	2.4
Vacuum probe samples at 4–12 m depth	83.5	1.1	7.0	7.7	0.2

^a See text for explanation of the types of samples, location or time grain sampled.

residues outwith bins, grain residues in empty bins and the first grain passing through the discharge spout, but high in wheat stored in bins. *S. oryzae* populations were low in the wheat stored in bins, but high in grain residues outwith bins, grain residue in empty bins and the first grain passing through the discharge spout. Insect densities in the more accessible grain residues inside empty bins and outside the bins, and the first grain passing through the discharge spout, were ten times higher than those in the wheat stored in bins (Reed *et al.*, 2003; Arthur *et al.*, 2006). The large numbers of insects in the first grain discharged from the discharge spout may be the result of insects from grain residues infesting grain stored near the bottom of the bin.

Cleaning the empty bins before refilling resulted in a lower insect density in the discharge spout sample from new grain stored in these bins for a period of up to 3 months. Insect densities in grain residues outside bins were higher in samples collected at the ground or subterranean level (discharge spouts, residues in empty bins and spills in the basement or tunnel) than at the top of the elevator, where much of the grain being conveyed is new grain being loaded into bins. Investigators concluded that routine sanitation practices, including prompt clean-up of spills, thorough cleaning of empty bins, and periodic flushing of discharge spouts, should greatly reduce the resident population of stored-grain insects at elevators.

The numbers of *R. dominica* and *T. castaneum* in wheat delivered from farm to country or terminal elevators were higher and the numbers of other species were lower than in wheat delivered from country elevators to terminal elevators. The overall mean insect density in wheat delivered from farms (4.18 ± 1.38 SE, $n = 909$) was higher than the overall mean insect density in wheat delivered from a country elevator (0.50 ± 0.06 SE, $n = 4554$). Higher mean insect densities in farm-stored wheat may in part be a result of the grain being stored in smaller bins where grain is more accessible to insects. In both cases, 80% of the wheat samples did not have insects. In bins that had received wheat at harvest time, the wheat between 12 m below the surface and 1 m up from the bottom was generally inaccessible to insects until the grain was moved. During several months of storage, this grain had a lower insect density than grain closer to the top and bottom surfaces. In wheat stored in elevator bins in Kansas and Oklahoma, *C. ferrugineus* was more prominent in the top 3.7 m, while *R. dominica* was more prominent at 4–12 m.

Natural Enemies of Stored-grain Insects

Hymenopteran insect parasitoids of pests were found in the wheat stored in bins at 13 out of 16 elevators in Kansas (Reed *et al.*, 2003). *Cephalonomia waterstoni* and its host, *C. ferrugineus*, were most prevalent in grain samples from wheat stored in bins or grain residues in empty bins, while *Anisopteromalus calandrae* and its host, *S. oryzae*, were most prevalent in samples from grain residues found outwith bins (Arthur *et al.*, 2006; Table 12.4). *Theocolax elegans*, a parasitoid of *R. dominica*, and *Habrobracon hebetor* Say, a parasitoid of the Indianmeal moth, *Plodia interpunctella*, were found in much smaller numbers.

Parasitoids were found in the grain residues outwith bins at all nine elevators from which grain residues samples were collected, and they were found in 1.6–9.4%

Table 12.4. Species composition of beneficial insects in various types of grain samples from elevators in Kansas.

Location of sample	Percentage of each beneficial insect species			
	<i>H. hebetor</i>	<i>A. calandreae</i>	<i>T. elegans</i>	<i>C. waterstoni</i>
Grain stored in bin	10.39	14.77	1.17	73.67
Grain residue from empty bin	7.40	12.50	1.00	79.10
Grain residue from outwith bin	0	89.93	3.90	6.17

of the grain samples taken at any one elevator. Because of the small size of parasitoids and their tendency to leave grain samples, their prevalence was probably underestimated. However, the numbers and prevalence of parasitoids indicate that they are important in reducing the numbers of insect pests at elevators.

Current Insect Pest Management Practices at Elevators

Aeration, sanitation and fumigation are the primary methods used to manage stored-grain insects at elevators in the USA (Hagstrum *et al.*, 1999). Treating grain with a residual insecticide or inert dust as a protectant is less common at elevators (Subramanyam, 2003) than on farms. In a 1997 survey based upon 1956 responses to a questionnaire from elevator managers in 14 states, representing 82% of the wheat produced in the USA, malathion was used on 1.5% of the wheat, chlorpyrifos-methyl was used on 1.4% and inert dust was used on 0.2%.

One potential disadvantage of protectants is that grain may be treated more than once, resulting in insecticide residues exceeding tolerances of 8 ppm for malathion and 6 ppm for chlorpyrifos-methyl. Pesticide data programme residue analysis of 1563 wheat samples from 29 states between 1995 and 1997 showed that 0.002–7.600 ppm of malathion were found on 68–71% of samples, that 0.002–3.300 ppm chlorpyrifos-methyl residues were found on 52–73% of samples and that 40–48% of samples had residues of both insecticides. These residues must be the results of protectants being applied on farms before wheat is delivered to elevator.

The cost of aeration systems is often justified as a means of managing grain moisture, especially in autumn crops. In the Kansas/Oklahoma study, 29% of the concrete bins and 44% of the steel bins at elevators in Kansas, and 18% of the concrete bins and 50% of the steel bins at elevators in Oklahoma were equipped for aeration. Automatic aeration controllers can be used to cool wheat during the summer and autumn by running fans only when air temperature is appropriate for the cooling of grain.

Aeration was tested as a way of managing insects in stored wheat. In a Kansas study in a large upright bin equipped with 20-HP, positive-pressure aeration fan located near the bin floor, a 5-HP fan extracting air on the roof and an aeration controller, two aeration fronts were moved through the grain cooling it from 28.9 to 18.3°C by the end of October. The principal insect pest species cannot survive and

reproduce at this temperature. The cost of aeration was US\$188 per bin, or US\$0.004 per bushel.

Sanitation programmes remove residual grain or grain dust so that insect populations cannot reproduce in them. Sanitation alone cannot eliminate insect populations, but it does reduce populations and may improve the effectiveness of other pest management methods. Inspection of elevators in Kansas has shown that spilled grain residues usually consist of only a few bushels per elevator and that these usually were cleaned up in less than a week. However, the grain residues were sometimes swept into the nearest bin without killing the insects infesting them.

Fumigation of grain with phosphine to kill insect pests is most effective when a lethal dose is maintained throughout the commodity and storage structure for the period required to kill the insects (normally 3–5 days). To maintain this lethal concentration for several days, the storage structure must be sealed or fumigant must be added from pressurized cylinders to replace the fumigant that leaks out of the structure. Studies showed that the fumigation was often carried out on a calendar schedule instead of when it was needed or when it would have been most effective. Our AWPM project found that wheat was fumigated throughout the storage period in Kansas (see Fig. 12.4).

However, only a small portion of the wheat stored in the nearly 486,000 t (18 million bushels) of storage capacity at 13 elevators was generally fumigated each month. Some of the wheat stored for a long time may be fumigated two or three times. The peak number of fumigations in September was a result of managers fumigating wheat before the autumn harvest of maize, grain sorghum and soybeans. In a 1997 nationwide survey, elevator managers in the USA indicated that phosphine was

Fig. 12.4. Total bushels of wheat at 13 elevators in Kansas fumigated each month, June 1998–June 1999.

used on only 11.5% of wheat (Subramanyam, 2003). Phosphine fumigation costs US\$0.33 to 0.43/ton when probed into the grain stored in a steel bin, and US\$0.75 to 1.10/ton when fumigant was added to the grain stored in concrete bins by moving the grain to another bin (Hagstrum and Subramanyam, 2006). The cost of moving grain is US\$0.48 to 0.67/ton.

Phosphine fumigants leave no pesticide residue on grain, so insects from other bins and grain residues can infest the grain as soon as the fumigant has dissipated and when the ambient air temperature is high enough for insect movement. Also, because of the difficulty of sealing bins, all of the insects are not killed during a fumigation of a typical elevator bin. The densities of the major insect pest species in wheat stored at two elevators in Kansas, where all of the bins were fumigated, were reduced by 97–99%. In Oklahoma, no insects were detected after fumigation in eight out of 11 bins, but insects were detected in the other three bins (Phillips *et al.*, 2001). These insect pest populations will often recover after fumigation.

Maintaining fumigant concentrations is most difficult near the grain surface, where insect densities are highest (see Fig. 12.3). Studies (Reed, 2006; Flinn *et al.*, 2007c) have shown that the optimal method of determining where to apply the fumigant when grain is turned from one bin to another is based on the difference between grain temperature and outside air temperature. When the post-turn grain temperature and the air temperature during the fumigation period are similar, distributing the fumigant evenly throughout the full depth of grain provided the greatest chance of success. When the grain was significantly warmer than the average outside air temperature during the fumigation period, applying the fumigant to grain loaded into the bottom half of the bin was most successful because air currents moved the fumigant towards the top of the grain mass.

Fumigating only the bins in which grain has high levels of insect infestation will minimize the use of pesticides, the cost of pest management and the rate at which insects become resistant to pesticides. Minimizing the use of pesticides in the USA is important because insects have already started to become resistant (Zettler and Cuperus, 1990). Timing of fumigation is very important. Fumigating too early can result in insect populations recovering before grain cools in the autumn and winter, and a second fumigation will be needed. Fumigating too late can result in substantial economic losses attributable to insects. Killing insects resistant to pesticides by aerating to cool the grain in the autumn and winter will also slow the development of resistance.

Areawide Pest Management

Areawide pest management (AWPM) reduces the overall insect pest levels over time by managing them over a wide area. Stored-grain insect pests are very mobile and can quickly reinfest grain that has been disinfested (Hagstrum and Subramanyam, 2006). An example of a successful AWPM programme is the one implemented for the central bulk grain handling organization in Queensland, Australia following two storage seasons (1989–1991) during which approximately 60% of storages were infested (Bridgeman and Collins, 1994).

The widespread use of the residual insecticides bioresmethrin and fenitrothion as grain protectants in Australia had led to complacency among managers, and sanitation had gradually declined over several seasons because of heavy reliance upon these residual insecticides. According to Bridgeman and Collins, the development of insecticide resistance, inadequate sealing of structures for fumigation and the practice of receiving or shipping grain from a storage facility before fumigation had been completed also contributed to poor insect pest management.

The project addressed these issues by developing written standards for sanitation, providing training and conducting periodic sanitation audits. Amorphous silica was used instead of residual insecticides to treat storage facilities and grain was cooled by aeration. Additional sealing was carried out to increase the effectiveness of the fumigation. Farmers and private grain traders were encouraged to use pest management methods other than residual insecticides and to deliver residue-free grain. An insect-trapping programme was developed to provide early warning of insect problems so that the timing of insect pest management could be optimized.

As a result of the programme, the percentage of storage facilities that were infested was reduced from 60 to 16. The percentage of storages in which residual insecticide residues were detected decreased from 90 to 30, and the cost of insect pest management was reduced from A\$1.50 to 0.60/ton (approximately 37 bushels) of wheat.

During the 2000–2001 and 2001–2002 crop years, all of the wheat at 28 elevators in Kansas and Oklahoma was sampled for insects with a vacuum probe at a sampling rate of 0.07–0.13 kg/ton (Flinn *et al.*, 2003a, b, 2007a). Insect numbers in grain samples collected by vacuum probe from the top 12 m (40 feet) of grain were highly correlated with the insect numbers in grain samples taken as the bin was unloaded ($r^2 = 0.79$) (Reed *et al.*, 2001). Also, 96% of *C. ferrugineus* and 94% of *R. dominica* were found in the top 12 m of the grain stored in bins (see Fig. 12.3). Thus, the vacuum probe provided a convenient and reliable method of routinely sampling the grain for insects without having to move the grain.

Vacuum probe sampling of grain stored in bins at elevators for insects cost US\$0.0092 per bushel of grain at a sampling rate of 0.07–0.13 kg/ton (B. Adam, 2006, personal communication; Adams *et al.*, 2006). This includes the labour cost to set up and take down the sampling equipment (2.5 h), taking grain samples (2 ± 1 min per sample), sieving insects from the grain sample (0.4 ± 0.3 min per sample) and counting the numbers of each insect species in the grain sample (3.01 ± 0.93 min per sample). This also includes the purchase of a US\$8000 vacuum probe sampler with an expected lifespan of 10 years. If the cost of the vacuum probe is not included, sampling costs US\$0.002/bushel.

Decision support software (STORED GRAIN ADVISOR PRO, <http://ars.usda.gov/npa/gmprc/bru/sga>, Flinn *et al.*, 2007b) was developed for wheat stored at elevators. This program uses information on insect density from vacuum probe grain samples to make decisions for each bin at an elevator. It also uses a computer simulation model to forecast the insect-related risks based upon the current estimates of insect density, grain temperature and grain moisture. Risk analysis is presented graphically to the elevator manager as a bin layout diagram. The manager is also given a printed report with insect pest management recommendations and economic analysis for each bin.

For the 533 bins at 28 elevators in Kansas and Oklahoma sampled to a depth of 12 m every 6 weeks by vacuum probe, decision support software was used to predict which bins were at low risk of economic losses attributable to insects (< 2 insects/kg predicted in 1–2 months), moderate risk (2–10 insects/kg predicted in 1–2 months) or high risk (> 2 insects/kg when sampled and 10 insects/kg predicted in 1–2 months). For bins with high risk, fumigation was recommended, and for the bins with low or moderate risk, sampling again in 6 weeks was recommended. STORED GRAIN ADVISOR PRO failed to predict when grain was at a high risk for only two bins, and in both cases the insect density was high only near the grain surface, suggesting recent insect immigration. Probe traps could be used to detect these re-infestations near the surface (Toews *et al.*, 2005).

Sampling of the 533 bins discussed above showed that only a small portion of the bins at each elevator needed to be fumigated at any one time (see Table 12.5). The percentage of bins needing fumigation increased from 1.7% in June to 19% in October, and then tended to decrease from November to May. This reduction was perhaps the result of heavily infested wheat being fumigated by elevator managers who detect insects by monitoring grain temperature for evidence of heating.

Because the percentage of bins at an elevator that needed to be fumigated varied from 0 to 60 and averaged 10, sampling to locate infested bins was cost effective. Early fumigation of the grain stored in these few bins may reduce the overall insect infestation at elevators. The remaining bins at an elevator may not need to be fumigated at all, because fumigating the few bins that had high insect densities earlier should reduce insect immigration into the other bins and thus prevent insect density in these bins from reaching unacceptable levels. Survival of the natural enemies in the bins that are not fumigated may also reduce insect populations. Thus, risk analysis software can improve pest management by predicting when insect pest populations will reach economic injury levels and by reducing the amount of grain fumigated. The areawide, sampling-based pest management approach can be used cost-effectively at a single elevator (each bin representing a field and all of the bins representing a large geographical area) as well as throughout the wheat marketing system.

Fumigating the grain in all of the bins at an elevator storing 19,048 t (700,000 bushels) of wheat would cost US\$14,000. However, when the elevator manager knows that only three out of 30 of these bins are likely to have insect densities of ≥ 2 insects/kg during the following 2 months, fumigating these three bins would cost only US\$1400 and the cost of fumigation would thus be reduced by US\$12,600.

Table 12.5. Number of bins at each elevator in which wheat required fumigation (data from 28 elevators in Kansas and Oklahoma).

Number out of 100 bins	Frequency (%)
0–10	71
11–20	12
21–40	13
41–60	4
>60	0

Commercial Scouting and Consulting

With vacuum probe sampling of all bins and the decision support software discussed above, a private consulting company has provided scouting services to more than 70 elevators in Kansas, Oklahoma and Nebraska during the past 5 years (Flinn *et al.*, 2007b). The sampling programme has improved insect pest management by ensuring that fumigation is done at the time when it will be most effective. Scouting may have helped to reduce the average incidence of insect-damaged kernels by as much as 24%. The average number of IDK was 2.5 per 100 g of wheat during the first year of scouting and 1.9 per 100 g of wheat during the second year.

Initially, managers often did not follow the recommendations of scouting reports, but after receiving several reports many of the managers started following the recommendations. Managers have used the improved grain quality information from the scouting report for the full bin depth to better merchandize their grain. Information about current insect infestation levels and forecasts of future insect infestation levels allow elevator managers first to sell the grain that is most likely to need fumigation if it would have been kept for another month or more.

Conclusion

When wheat is mixed with wheat from other locations as it moves through the grain-marketing system insect infestation can be spread to larger quantities of wheat, increasing the overall cost of insect pest management. In Kansas and Oklahoma, insect infestations are currently managed primarily by calendar-based fumigation of all of the wheat at an elevator. Grain is not sampled to determine the most effective time for fumigation. Insufficient sealing and poor timing of the fumigations reduce the cost-effectiveness of fumigation. The low sampling rates used for grain inspection result in large numbers of insects being shipped with the wheat, thus spreading the insect infestation throughout the marketing system.

Calendar-based fumigation of all of the grain at an elevator is not cost-effective because usually only a percentage of the bins require fumigation at any one time. Delaying the fumigation, when possible, until the autumn has several benefits: (i) the grain can be cooled with aeration after an autumn fumigation, which decreases subsequent population growth; (ii) insect immigration rates into grain bins in the autumn and winter are lower than during the summer; and (iii) the necessity for a second fumigation is greatly reduced because of (i) and (ii). Areawide, sampling-based pest management at each elevator or across the grain-marketing system using decision-support software can minimize the cost and maximize the effectiveness of insect pest management. In addition, it should reduce the risk of economic losses due to insects, the amount of wheat that is fumigated and the frequency of fumigation.

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