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Insect detection and density estimation in stored grain bins: is it a needle in a haystack or an elephant in a room?

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Abstract

Detection of insects and accurately estimating their densities are the foundation of stored-grain management programs. To accurately detect insects and estimate their densities, understanding of insect movement and distribution within grain bulks is required. The quantified and qualified relationships among insect movement, distribution, and density estimated by sampling and trapping help to develop this program. In this review, we 1) investigated the difference among insect movement and distribution inside small-scale tests and full-scale field bins based on published literature; 2) examined the basic assumptions and conditions which must be satisfied to estimate insect distribution and density by using sampling and trapping methods; and 3) analyzed the strategy of sampling and trapping under defined conditions. We concluded that: 1) normally used sampling methods could not be used to detect insects and estimate their density and distribution when insect density was less than one insect per kilogram of grain; 2) sampling methods cannot be used to verify the accuracy of trapping methods due to the low detection probability of the sampling method; 3) using traps as a sampling tool might be a practicable method; and 4) trapping data could be used to estimate insect density and distribution after the relationship between trap capturing frequency and insect densities around traps was mathematically established.

Keywords: insect movement, insect distribution, sampling, trapping, accuracy

1. Introduction

A successful program for stored-grain management relies on an effective monitoring program that provides information on not only the number and type of pests present inside samples or traps but also insect density and distribution, changes in pest populations over time, and locations and routes of entry into grain bulk. This monitoring program requires the understanding of insect movement and distribution inside stored grain bulks and sampling and trapping principles because the quantified and qualified relationships among insect movement, distribution, and density estimated by sampling and trapping will help to develop this monitoring program.

To detect the existence of insects and estimate their density, sampling or trapping is usually conducted. The basic assumptions for these practices are: 1) data collected by sampling and trapping can be used to estimate insect density inside entire bins; 2) sampling and trapping do not alter the insect density and their distribution; and 3) insect density and their distribution will not

change during a sampling period or insect movement will not influence the estimated insect density and distribution. The assumption 3 might be true when the sampling period is short, such as less than a few hours when sampling data are used to estimate insect densities. However, insect movement will affect the density estimation by using traps because some insect species (such as adults of *Cryptolestes ferrugineus*) move more than half meters in one hour (Jian et al., 2002, 2003). The assumption 2 might be true also when sampling size is small and sampling data are used. Whether the assumption 1 is true or not will depend on sampling size (Davis, 1994; Jian et al., 2011a; Jian et al., 2014a and b), trapping efficiency (the proportion of the insects near a trap that are captured) (Hagstrum, et al., 1985; Hagstrum, et al., 1998) and frequency (how often the insect around the trap can be trapped), and effective distance of trapping (the maximum distance at which insects can be trapped over a given time period).

Insects move inside stored-grain bulk in response to biotic or abiotic factors such as temperature and moisture gradients in the stored grain (Jian et al., 2009; Jian and Jayas, 2009), grain odors, CO₂ gradients (White et al., 1993), pheromones and kairomones. This movement increases the difficulty of making density estimates and sampling protocols because the overall insect density inside the stored grain bin does not change whereas densities at different locations change. Insect movement has been effectively used to trap insects, even though trapping efficiency and effective distance of trapping are not fully understood. For an assumed accuracy of insect density estimation, different insect distributions require different sampling sizes (Davis, 1994; Hagstrum et al., 1985; Jian et al., 2014 a and b). Trapping efficiency and frequency might be influenced by insect species, distribution and their behavior (Jian et al, 2014 a and b). Therefore, effect of insect movement and distribution on the detection of insects and density estimation by sampling and trapping methods should be considered.

Our purpose in this paper was not to present an exhaustive list of references related to insect movement and distribution, sampling and trapping; rather, our objectives are to: 1) investigate the difference among insect movement and distribution inside small scale tests and full scale field bins based on published literature; 2) examine the basic assumptions and conditions which must be satisfied to estimate insect distribution and density by using sampling and trapping methods; and 3) analyze the strategy of sampling and trapping under specified conditions. Based on these examinations and analysis, a strategy of sampling and trapping for the low insect density (<1 insect/kg of grain) was suggested.

2. Movement and distribution of insects

2.1. Insect behavior in small-scale chambers

Adult stored-grain insects move inside grain bulks in response to temperature gradients (Flinn and Hagstrum, 1998; Flinn and Hagstrum 2011; Jian et al., 2002; 2003; 2004 a and b; Jian et al., 2005a, b, and c), moisture differences (Loschiavo, 1983; Parde et al., 2004; Jian et al., 2005a), fumigant concentration gradients (Bell, 1986), different grain types (Jian et al., 2005 b), CO₂ gradients (White et al., 1993; Parde et al., 2004), and volatiles released by grain, fungi, or insects (Cox and Parish, 1991). Insect species, age and insect density also influence movement and distribution (Jian et al., 2005c) even though dockage (Jian et al., 2005 a), insect density (Jian et al., 2004 a), and sex (Jian et al., 2005 c) are minor factors influencing their movement and distribution. Individual adults of different species may have similar response to the environmental factors but their group behaviors may be different (Table 1). For example, stored-grain insects usually have a clumped distribution inside stored-grain bulks. The level of

aggregation of various species is different and they may have different levels of auto-correlation with adjacent locations (Table 1). The volatiles produced by one species might influence the behavior of other species. These population behaviors among species may result in different population distribution inside stored-grain bulks.

Table 1 Comparison of population behavior of stored-grain insects inside a bin filled with 1.5 t wheat or maize.

Species	Location correlation ^a	Continuous ^b	Aggregation	Source
<i>Cryptolestes ferrugineus</i>	Better correlated at medium or high density and in the vertical direction.	Does not exist or weak	Clumped with 95% chance and uniform with 5% chance. Highest at low insect density	Jian et al., 2011b
<i>Oryzaephilus surinamensis</i>	Prefer centre locations and top layer, auto-correlated in any direction	Does not exist	Highly clumped at low and minimum insect density	Jian et al., 2012b
<i>Rhyzopertha dominica</i>	Auto-correlate in any direction	Exists	Highly clumped at low and minimum insect density	Jian et al., 2012a
<i>Sitophilus oryzae</i>	Prefer centre locations and top layer, Auto-correlated in any direction	Does not exist	Highly clumped at low and minimum insect density	Jian et al., 2012b
<i>Tribolium castaneum</i>	Does not correlate in any direction	Exist	Highly clumped at low and minimum insect density	Jian et al., 2012c

^aAuto-correlate with those in adjacent locations.

^bTemporal continuous property.

Insect movement and distribution studies are usually conducted in small containers or columns because of the constraints of full-scale field tests such as counting insects in all of the tested grain bulks. These small-scale studies demonstrate some behavior of the tested insects and explain some of the results found inside stored-grain bulks. For example, Jian et al. (2006) found that adults of *Cryptolestes ferrugineus* (Stephens) introduced in a 0.6 m diameter and 1.12 m high wheat column had a distribution similar to those introduced in 0.1×0.1×1.0 m columns.

2.2. Insect behavior in full-scale field bins

The behavior characterized in small-scale experiments might not explain all of the insect movement and distribution found in full-scale stored grain bins. For example, insect distribution in the horizontal direction is different from that in the vertical direction (Jian et al., 2006) and their movement and distribution is modified by the size of the grain mass (Jian et al., 2011a and b, 2012a, b and c) and configuration of storage structures (Perez-Mendoza et al., 2004; Athanassiou et al., 2003). Each species follows a pattern of distribution under a small-scale experimental set-up (Jian et al., 2011b; 2012a, b, c). These patterns therefore may not explain that species composition changes with grain depth inside stored grain bins (Flinn et al., 2010). Hagstrum et al. (1985) found that the density of *Cryptolestes ferrugineus* was greatest in the upper grain layer and decreased exponentially with grain depth. Adults of *C. ferrugineus* prefer moving down inside small columns, and this downward movement may be caused by a drift effect (Jian et al., 2006, 2009). This behavior could not fully explain their distribution inside a test bin filled with 48 t of wheat (Jian et al., 2012d). Inside the bin, adults moved down in the first week after they were introduced

regardless of the temperature distribution. One week after the introduction, adults gradually moved up and their distribution followed the temperature gradients with most adults being captured from the warmest layer. However, offspring of the introduced adults followed the temperature gradients except in the top layer which had the warmest grain (Jian et al., 2014a). Inside an elevator in the USA, the numbers of insects generally tended to decrease with the depth below the grain surface (Mahmood et al., 1996, Flinn et al., 2010). After 10 months of storage, very few insects were found in samples collected from depths greater than 12 m (Flinn et al., 2010). This suggests that insects infest wheat stored at the elevator after it has been loaded into bins and then disperse down into the grain (Flinn et al., 2003). Adults of *C. ferrugineus* have 0.44 m/d average net-displacement due to their random movement and bias of temperature gradients (Jian et al., 2009). Under this net displacement, adults should reach 20 m in less than 47 days. These facts suggested that adults might lay eggs in the top grain layer, and the offspring tended to remain there, unless the temperature gradient changed. In that case they may move towards the warmer and more central regions of the grain mass in the fall.

These differences might be explained by the difference among the small-scale experiments and the field bins, such as different temperature and moisture gradients, different fungi and insect species present, convection currents, trace amounts of chemicals (such as pheromones and volatiles) flowing with the convection currents, insect ability to cue orient, and detect grain volatiles, and interaction between species (Jian and Jayas, 2009; Jian et al., 2009). Therefore, adults reared under laboratory condition and released into grain bulk will probably act differently than their offspring developing under field condition because the behavior of movement of insects may also be related to their adaption to the grain storage ecosystem. For example, stored-grain beetles are negatively phototaxic and seek out refuges providing close physical contact with their body (Cox and Parish, 1991). There will be an advantage to insects that commence dispersion before conditions deteriorate too far (temperatures, moisture content and insect density becoming too low or too high), thus improving their chances of finding more suitable conditions. Dense populations of *Tribolium castaneum* (Herbst) release benzoquinones causing the beetles to migrate from the crowded area (Faustini and Burkholder, 1987). One species may affect the distribution of another species because odors released by one species might influence the behavior of other species. Therefore, the interaction among biotic and abiotic factors, the survival requirements, and their adaption to this environment should be considered as they affect their movement inside full-scale storage bins.

2.3. Mathematical models to understand insect movement and distribution

Understanding insect movement inside full-size field bins will provide information on insect distribution. This information can be used to find the difference in their movement between small and large size bins. A strategy of sampling and trapping inside different size bins can be developed by using this information. Therefore, full-size bin testing is required. Even though insect distribution inside full-size field bins had been studied (Hagstrum et al., 1985;1998; Hagstrum, 2000, Flinn et al., 2003; 2010; Athanassiou, et al., 2003), the information provided by these studies is limited by the small sampling size because a full-scale field test is time-consuming and limited by finances and human ability to process samples. Mathematical models can be used to simulate field conditions and interpret these interactions because mathematical models can handle these fluctuating factors and the interactions among factors (Jayas, 1995). For example, distribution and dispersal of the *C. ferrugineus* adults in 1.0×1.0×0.1 m chambers follow a diffusion pattern under constant environmental conditions (Jian et al., 2007). This

diffusion pattern is modeled by Jian et al. (2008). The estimated parameter(s) in a diffusion equation is related back to the underlying rates and processes of insect movement. The model is combined with a temperature model and the population dispersal of adult *C. ferrugineus* in stored-wheat columns and boxes with or without temperature gradients is accurately predicted (Jian et al., 2008). Mani et al. (2001) combined an insect movement model with heat transfer and population dynamic models. This combined model showed that a minimum of ,1300 adults of *C. ferrugineus* introduced in the early fall at the top center of an unventilated 6-m diameter wheat bulk initially at 30°C caused hot spots in late winter under Winnipeg, Manitoba weather conditions. A simulation model was developed for predicting *Rhizopertha dominica* (F.) population dynamics and vertical distribution in concrete grain bins (Flinn et al., 2004). The model assumed different immigration rates of adult pests into top layers of the grain bulk. The model accurately predicted insect vertical distribution and insect density (Flinn et al., 2004). To correctly understand and predict insect movement and distribution, more models (such as pheromone diffusion, hot spot development, insect development and competition, insect response to mould and volatile chemicals, insect movement and distribution under multi-species and dynamic density conditions) are required. The developed models could be used to develop sampling and trapping plans.

3. Insect movement, distribution and sampling strategy

3.1. Conventional sampling method

The population density inside stored grain bins is rarely determined by counting individual insects inside all the stored grain. To detect insects and estimate their density inside a stored grain bulk, the conventional method is to sample the grain using a grain probe or vacuum probe sampler at multiple locations in the grain mass. The insects inside the samples are used to estimate insect densities and their distribution patterns. The information or conclusion drawn from these sampling data was further used to develop future sampling plans. Insects usually have clumped distribution (Jian et al., 2011 b, 2012 a, b, c) and heterogeneous or homogeneous distribution might be assumed before sampling. Even under the assumption of homogeneous distribution of insects, estimating insect density with reliable accuracy requires to sample more than 1,000 kg of wheat inside a mid-sized farm bin with about 150 t grain (Hagstrum et al., 1985; Jian et al., 2011a; 2014 a and b) and separate the insects from the sampled grain. More samples will be required if insect distribution is not homogeneous such as clumped distribution. The probability (p) of insect detection inside samples can be calculated as: $p = 1 - (1 - \theta)^v$ (Hunter and Griffiths, 1978). Where, θ is the sample fraction and v is the number of insects in the samples. To detect the existence of insects, the minimum number of insects inside all samples is 1 ($v = 1$). If 0.37 kg of grain is sampled from 33 t of grain as recommended by the Canadian Grain Commission ($\theta = 0.00001$), the detection probability (p) is 0.001%. This indicates that there is little chance of finding insects. Therefore, different sampling strategies and methods are suggested, such as binominal sampling (presence or absence of insects inside the samples) (Hagstrum et al., 1985) and sequential sampling (Subramanyam and Harein, 1990; Subramanyam et al., 1997). These suggested sampling strategies and methods are only practicable when insect density was higher than 1 insect/kg of wheat (White and Loschiavo, 1986; Wilkin and Fleurat-Lessard, 1990; Jian et al., 2014 a and b) because one probe sample with 0.25 kg sample unit does not accurately predict the insect density in another grain sample taken at a distance of 30 cm (Hagstrum et al., 1985). This large variation between samples is caused by the clumped insect distribution (Jian et al., 2011 a; 2012 a, b and c). Several researchers suggested that sampling

methods might characterize different insect distribution patterns (Stejskal et al., 2008; Lukas et al., 2010, Jian et al., 2014 a and b). Therefore, Jian et al. (2014b) suggested that using sampling methods to estimate insect densities with less than 60% of percent relative variance might be impractical when insect densities were less than 1.0 adult/kg. Sampling grain with higher than 1.0 insect/kg of grain will not be discussed in this article because: 1) high insect densities pose potential risks to grain quality during storage and to grain acceptance during selling; 2) sampling grain with high insect densities require less samples with small sample units; and 3) the density of 1 insect/kg of grain is used as the economic threshold for an IPM program in some countries such as USA. The main objective of sampling is to detect insect existence and estimate their distribution and density when their densities are low. The predicted insect density based on the sampling data under low insect density can be used to design an IPM program based on the economic threshold.

3.2. Basic assumptions of sampling

Measurements taken to estimate population density fall into three groups: absolute methods, relative methods, and population indices (Ruesink and Kogan, 1982). Absolute methods estimate insect density in the grain storage bins by counting all the insects inside the stored grain. Relative and population index methods estimate insect density by sampling. Estimation of insect density from samples cannot be applied to the absolute estimation of insect density inside the entire bin without correcting of the insect's behavior and/or the effect of habitat (Ruesink and Kogan, 1982; Jian et al., 2011a). There are studies to estimate insect densities from samples (Athanasios et al., 2003; Flinn et al., 2010; Hagstrum et al., 2010; Jian et al., 2011a; 2014 a and b; Hagstrum 2000; Hagstrum et al., 1985). Almost all of these studies used relative and population index methods because it is impractical to count all insects inside all of the stored grain. To convert the estimation from the samples to the estimation of entire bins, researchers or samplers will use statistical tools to estimate insect densities and distribution patterns with an assumption that the sampled population represents the population inside the stored grain bins (Fig. 1). This assumption is only true when the sample size and unit are big enough (Davis, 1994; Jian et al., 2011 a; 2014 a and b). Jian et al. (2014 b) recommended that 2.5 to 7.5 kg sampling units and about 7.5% grain should be sampled to detect insects at 0.1 adults/kg densities with clumped distribution. When insect densities are ≤ 0.5 adults/kg, 10.0 kg sampling units and about 37% grain should be sampled to accurately characterize insect distribution. This means that more than 7 t and 37 t of grain inside a 100 t grain bin should be examined to detect the existence of the insects and estimate their density, respectively. A farm bin with 6 m diameter and 6 m grain height could store more than 100 t of wheat. Considering the work involved removing more than 7 t of grain, separate insects from the grain, and identify the separated insects, this is impractical. Therefore, the above mentioned assumption is rarely true during the practice of grain storage management when insect density is <1 insect/kg of grain. If this assumption is wrong, the sampling method cannot be used to estimate insect density and their spatial distribution inside entire bins (Davis, 1994; Jian et al., 2014 a and b).

If insect distribution is known, a sampling plan can be designed by taking advantage of the insect distribution, and hence sampling size and unit can be reduced. Even though stored-product insects usually have a clumped distribution (Jian et al., 2011b; 2012a, b, c), this clumped distribution is influenced by biological and physical factors such as insect densities, species, insect movement time, temperature and moisture contents, and management practice of the stored grain (such as turning). For example, the count frequency of the adults of *C. ferrugineus* fits the

model of negative binomial, positive binomial, and Poisson distribution only 22%, 14%, and 14% of the time, respectively (Jian et al., 2011b). For a clumped distribution, it is impossible to interpret degree of aggregation because the ratio of variance and mean of insect densities has no upper limit. Therefore, it is not reliable to assume a particular insect distribution before sampling. If insect distribution is not known before sampling, the conclusion based on the samples cannot be used for entire bins (Fig. 1).

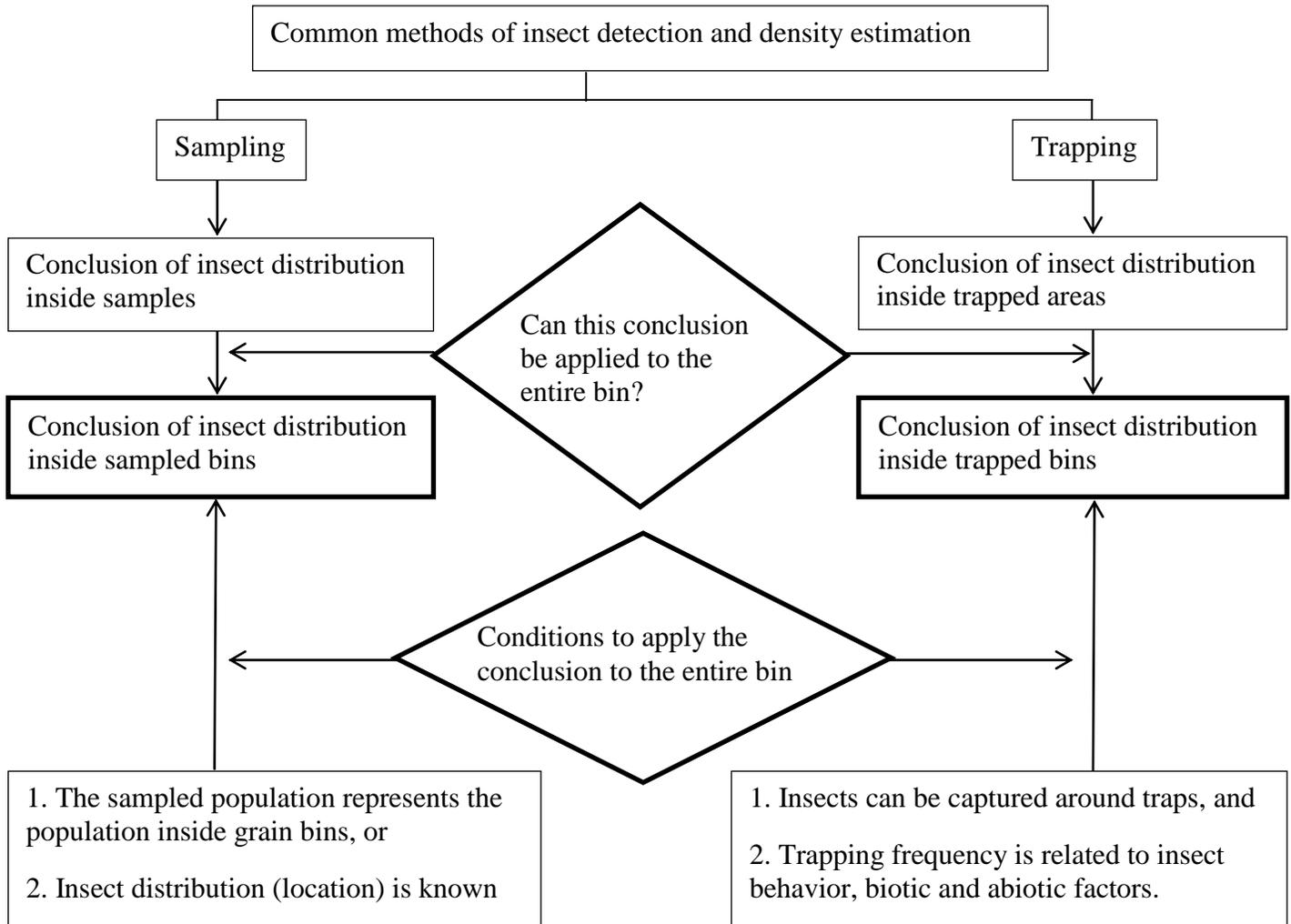


Figure 1 Conditions of estimation of insect densities and distributions inside the entire bins from grain sampling or trapping data.

3.3. Insect location and sampling strategy

If insect locations are known before sampling, the sampling size and unit can be reduced for the detection of insect existence and estimation of insect density. Therefore, even though sampling operators usually are not interested in insect distribution, information on insect distribution before sampling is required. Insect locations inside storage bins have been studied. Flinn et al. (2010) found very few insects in samples collected from depths greater than 12 m, and the

numbers of insects generally tended to decrease with the depth below the grain surface (Mahmood et al., 1996; Flinn et al., 2010). Inside flat storage facilities, the most abundant insect and mite species were found in the upper 0.5 m of the bulk, with some exceptions (Athanasidou et al., 2003) because different insects have different behaviors. The spatiotemporal distribution during the entire experimental period also varies according to the insect and mite species. Insect location is determined by insect behavior, biotic and abiotic factors. Therefore, insect movement and distribution inside bins under different environmental conditions should be studied in the future. If we have enough knowledge of insect behavior inside bins containing stored grain, we should be able to predict insect locations. This prediction can guide us to find the sample locations to detect the existence of insects, even though the estimation of insect density could not be applied to entire bins. If we apply the prediction to the entire bin, we might increase the prediction accuracy because the un-sampled locations have no or low numbers of insects. This sampling strategy based on the prediction of insect location can be used to further develop a sequential sampling plan. For example, sampling the top grain inside bins is usually suggested. If insects are found in the top layer, further sampling is required; otherwise, there is no need to sample other locations (Flinn et al., 2003).

4. Insect movement and trapping

4.1. Insects entering into stored grain

Insects entering stored grain structures and trapping strategy are well studied and documented. Studies show insects are most active and fly around grain bins during warmer months (Throne and Cline, 1994). More insects immigrate into large bins at the eaves compared with small bins because of their larger circumference (Hagstrum, 2000). Farm bins with high number of insects outside of storage facilities had high numbers of insects (Dowdy and Mcgaughey, 1994). The insect numbers captured by sticky traps located inside head spaces can be used to predict whether insects will be found in the grain sampled from inside the bin and different species have different prediction accuracy. This prediction cannot be used to recommend a treatment decision because grain temperature and moisture content will govern whether the insects can survive inside the bin. This prediction accuracy is increased if mean grain temperature and maximum moisture content are considered (Hagstrum et al., 1994). Therefore, trapping can be used to detect insects entering stored grain bulks.

4.2. Detect insects using trapping inside stored-grain bulks

Insect movement behavior inside stored grain bulks is often used to capture insects by using traps under both laboratory and field conditions. Loschiavo and Atkinson (1967) first described a grain probe trap. Several studies (White et al., 1990; Toews and Nansen, 2011) provide a comprehensive review of trap development, construction, and factors affecting usage of traps. Accuracy for the detection of insects and estimation of density by trapping method has been compared with sampling methods. Lippert and Hagstrum (1987) concluded that a trap was twice as likely as the grain probe to detect an infestation. Gates (1992) studied the insect population dynamics by using pit-fall probe traps, 0.5-kg probe samples, and 1- to 2-kg vacuum samples in two commercial bins. Probe and vacuum samples were not as sensitive as traps (Lippert and Hagstrum, 1987). This result agrees with similar studies by different researches (White and Loschiavo 1986; Flinn et al., 2009). Jian et al. (2014a) found the Insector® system (electronic trap) could detect adults within 6 h after introduction. Therefore, trapping is a more effective

method than sampling grain to detect the presence of insects if enough traps are installed and grain temperature is higher enough to allow insect movement.

4.3. Estimation of insect distribution inside bins using trapping

Possibility of using trapping to estimate insect density and distribution was investigated by several researchers. Hagstrum (2000) used five sampling methods (emergence traps, probe traps above the grain surface, probe traps within the grain mass, wing-type sticky traps, and grain trier) to measure insect distribution and abundance in wheat bins, and found using different methods resulted in different insect distribution and abundance results (Flinn et al., 2009). Athanassiou and Buchelos (2001) concluded that traps are poor indicators of population density. The Insector® system (electronic trap) can be used to characterize distribution of adults of *C. ferrugineus* (Toews and Philips, 2002; Jian et al., 2014a). The characterized adult distribution pattern was the same using either the data collected by the Insector® system or 15-kg samples, while 0.5-kg samples characterized different insect distribution patterns (Jian et al. 2014a). Therefore, there is no consistent suggestion or conclusion on how to use traps to obtain an estimation of population density inside entire bins.

Comparison between trapping and grain sampling inside full-size bins should be re-examined because small sampling size will result in a wrong estimation of insect density and distribution (Flinn et al., 2009; Jian et al., 2014b). For example, if the comparison is conducted inside a full-scale bin, the sampled portion of grain is usually less than 1% because of limitations of human and equipment resources for the separation and counting of insects from the sampled grain. Less than 1% of sampling portion will result in less than 1% detection probability when the true insect density is lower than 1 insect/kg of grain. If insect number at each location inside the tested bin is not known, this sampling portion will result in unreliable estimation of insect distribution. If sampling methods could not correctly estimate insect density and distribution, using sampling methods to verify the accuracy of the density estimation by trapping may not be reliable. Therefore, comparison of insect distribution estimated by trapping and sampling inside a full size bin might be impractical.

4.4. Conditions to estimate insect density using trapping

To detect insects and estimate insect densities by using traps, the following conditions should be satisfied: 1) traps can effectively capture insects around the traps (trap efficiency); 2) capturing frequency is related to insect density; and 3) these relationships can be mathematically quantified. It is well known that traps can capture insects; however, the relationship between capturing frequency, efficiency and distance of the insect from the trap is not known. Even though researchers have addressed the potential of using probe traps to estimate population density (Cuperus et al., 1990; Toews et al., 2005), many studies suggest that there is not always a good correlation between captures of stored-product insects and insect population densities (Vela-Coiffier et al., 1997; Hagstrum et al., 1998, Campbell et al., 2002a; Nansen et al., 2004; Toews et al., 2005; 2011). Therefore, whether conditions 2 and 3 are satisfied requires further study.

The difficulty to prove that conditions 2 and 3 are satisfied is that insect capturing frequency and efficiency can be influenced by several factors. For example, captures of *C. ferrugineus* in millet were 2-3 times greater than in wheat or corn (Cuperus et al., 1990). Estimation of insect density in stored grain using traps is likely to be inaccurate without careful consideration of these factors (Cuperus et al., 1990). Trap variation may be attributable to variation in trap frequency in response to environmental factors rather than to actual changes in population density because

insect density change is slow by comparison with the variation of most factors. These factors can be classified into three categories: trap design, insect movement domain and insect movement behavior. Trap design includes size and shape of trap, size and shape of holes inside the trap, and trap operation such as number of traps used (density of traps), trap location, and whether the trapped insects will be released or not. Insect movement domain includes shape and size of storage grain bulk, grain types, grain dockage and foreign materials. Insect movement behavior includes behavior of each species, speed of insect movement, response to living and nonliving factors such as gradients of temperature, moisture content and CO₂ concentration, inter/intra interaction between individuals under different densities, and movement of different ages of insects. Even though some factors (such as the factor of trap design) can be delimited during the quantifying of the relationship between trapping frequency and insect density, multifactor interaction will make this a challenge. Using trap to estimate insect density is also limited by the grain temperature and trap locations because insects cannot move far enough when temperature was less than about 15°C (Sinha and Watters 1985, Jian et al. 2003).

Even though it is challenging to quantify the relationship under multifactor interaction conditions, the very basic questions which can be used to simplify this work are: 1) does the modified insect behavior influence trapping efficiency (e.g., inside a small test chamber, insect movement is limited and trap efficiency might be too high)? 2) can insect density in the vicinity of the trap be predicted based on the trap capturing frequency? 3) if it cannot, how should it be extended? i.e. by applying more traps, or improving trap design; and 4) if conditions 1, 2 and 3 mentioned in the previous section are satisfied, what approach or algorithm can be used to estimate insect population density? Toews and Phillips (2002) found that there is a strong relationship between trap count and insect density inside 27.3 kg wheat. Jian and Larson (2006) found daily count of the Insector® strongly correlated to the insect density around the Insector® body in a range of 25 cm ($r = 0.97$). The correlation coefficient decreased when insect density was determined further away from the trap. Flinn et al. (2009) found the similar trend. Subramanyam and Harein (1990) found the accuracy of insect density estimations decrease with an increase in trap catch, but improved with an increase in the number of traps used. Therefore, only questions 1 and 4 should be investigated.

4.5. Using traps as sampling tool

If a trap can be used to estimate insect densities around the traps, trapping data can be used as sampling data at the fixed trapping locations. This is similar as if the stored grain is sampled at the trapping location continuously. If the insect density can be estimated at the trap location, increased number of traps will increase sampling size which will result in a higher accuracy of insect detection and density estimation inside the entire bin. Insect movement and distribution could also be determined based on the trapping data because the grain is sequentially and continually sampled with a high insect detection probability. Jian (unpublished data) developed mathematical models to predict insect densities by using the Insector® system. Multifactor interactions were considered in the developed mathematical models. Jian et al. (2014a) found the characterized adult distribution pattern was the same using either the data collected by the Insector® system or 15-kg samples. Therefore, using traps as a sampling tool might be a practical method.

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