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Final Report

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Better sampling strategies for stored grains

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1. Executive Summary

This is the final report for CRC30086 ‘Better sampling strategies for stored grains’. The project commenced in May of 2009.

1.1. *Aims and objectives*

To review current sampling methodologies and develop a flexible, statistically robust sampling system to calibrate and improve sampling strategies for the detection of post-harvest grain storage pests in the Australian grains industry.

Specific Project objectives

- Review random and strategic surveillance and sampling strategies currently used within the stored grains industry and determine their capacity to detect specific domestic grain pests.
- Identify and prioritise at-risk elements of the supply chain in which improved sampling strategies will maximise efficiency of EPP detection within existing resource constraints.
- Review current leading edge surveillance techniques in closely related fields, including probabilistic and non-probabilistic methodologies.
- Assess the accuracy of methods used to detect pest species.
- Identify a range of information resources that can be merged with existing or newly developed sampling methods to increase the power of analyses and provide evidence of freedom from specific EPPs.
- Appropriately modify existing sampling methodologies and develop new statistical sampling methodologies as needed that can be appropriately tailored to individual situations.
- Disseminate project outputs through multiple channels to target different audiences, allowing for the uptake of new methods.

1.2. *Key findings*

The review of stored grain sampling protocols in Australia, the first since Hunter and Griffiths (1978), suggests that current sampling protocols typically do not consider the known biological characteristics of the target organisms. This can impact on their accuracy for detecting pests, and suggested the need for the development of a new, more accurate sampling model.

Intake and outturn from on-farm storage and bulk handling facilities were identified as ‘at risk’ elements in the supply chain. Sampling methodologies currently vary significantly among regions and may not provide the level of detection that is required.

A statistical detection model (the Compound model) was developed for use in stored grain sampling. The model is the first to accurately incorporate species ecology and the spatial distribution of stored grain insects in grain bulks into sampling statistics.

Designed as a simple method to determine the number of samples required to maximise detections in grain bulks, this new approach showed an improvement of up to 400 percent in detection success over the Hunter and Griffiths (1978) model, and improved detection over a range of other statistical sampling models.

The model has been extended such that it can be used for IPM where detection at a zero tolerance threshold is not required.

1.3. Recommendations

For growers and grain handlers, sampling should be based on maximising detection of infestations at a given tolerance level.

With some knowledge of the possible extent of a putative infestation, sampling programmes for growers and grain handlers can be based on a fixed number of samples rather than altering sampling intensity in regards to load size.

On intake drawing six to seven samples will provide detection of moderate infestations with a probability of detection of 80%.

In storage sampling at between 50-75 samples per storage will allow for detection of infestations which are present in less than 5% of grain lot.

IPM requires knowledge of the presence and extent of any infestations in grain bulks, and this should be supported by sampling. The Compound model has been demonstrated to be robust and should be used as the basis for any IPM measures.

For a given total sample weight, taking more but smaller samples improves the probability of detection.

2. Aims and objectives

2.1. Overview

The biosecurity problem addressed in this project was the need to develop methods to accurately determine the presence of insect pests and Emergency Plant Pests (EPPs) within storages that threaten the grain industry. Statistical sampling models used in Australia do not consider sampling throughout the grain storage and supply chain. As such, the aim of the project was to review current sampling methodologies and if necessary develop new methods to assess current sampling regimes, and to develop new sampling protocols to provide statistical confidence for insect detections.

This necessitated the development of a new statistical sampling model. Rigorous testing demonstrated that the new model showed better capacity for detection of insect infestations than existing sampling models. This testing has subsequently been assessed and supported by international experts in the field of grains sampling. This theoretical development was an important and necessary step in the project.

The final phase of the project involved collection and supply of data by project members from different regions of Australia. Analysing this data with the new statistical sampling model would allow for regionally specific recommendations for sampling to be made.

A limited amount of data was either supplied or directly sampled. Pragmatic and logistical considerations prevented large quantities of data from being collected and supplied for analysis. Thus while general recommendations can be made, there are insufficient data to make detailed recommendations for sampling for individual regions.

2.2. Specific Project aims and objectives

To review current sampling methodologies and develop a flexible, statistically robust sampling system to calibrate and improve sampling strategies where required for the detection of post-harvest grain storage pests in the Australian grains industry.

Project objectives

- Review random and strategic surveillance and sampling strategies currently used within the stored grains industry, and determine their capacity to detect specific domestic grain pests.
- Identify and prioritise at-risk elements of the supply chain in which improved sampling strategies will maximise efficiency of EPP detection within existing resource constraints.
- Review current leading edge surveillance techniques in closely related fields, including probabilistic and non-probabilistic methodologies.
- Assess the accuracy of methods used to detect pest species.
- Identify a range of information resources that can be merged with existing or newly developed sampling methods to increase the power of analyses and provide evidence of freedom from specific EPPs.
- Appropriately modify existing sampling methodologies and develop new statistical sampling methodologies as needed that can be appropriately tailored to individual situations.
- Disseminate project outputs through multiple channels to target different audiences, allowing for the uptake of new methods.

Additional project objectives

- Development of a sampling methodology for use in Integrated Pest Management (IPM).
- Incorporate imperfect detection into sampling plans.

2.3. *Key findings*

Throughout the duration of the project each specific project objective was investigated. Below we present the key findings from each specific project objective.

This project has also resulted in the production of six peer reviewed journal articles, two published (Elmouttie et al. 2010, Hamilton and Elmouttie 2011) & four submitted manuscripts. Each manuscript has been related to specific project objective/s.

2.4. *Review random and strategic surveillance and sampling strategies currently used within the stored grains industry, and determine their capacity to detect specific domestic grain pests*

(See Hamilton, G. and Elmouttie, D. (2011). Insect distributions and sampling protocols for stored commodities. *Stewarts Postharvest Review. **7**:1-5).*

This project provided the first review of sampling methodologies used in the Australian post harvest grain industry since Hunter and Griffiths (1978). Unlike Hunter and Griffiths (1978) who focussed on the AQIS component of grain sampling, this project investigated the entire storage and distribution system.

Sampling in Australian grain storages has not always been conducted. The impetus to commence sampling was the development of a reputation for infested grain exports in the 1950s. In order to counteract the perception that Australia traded poor quality, infested wheat, the Export grain Regulations (1963) were established. These regulations originally prescribed that wheat should be sampled at a rate of 2.25L for every 33 tonnes loaded at export to determine if live insects were present. In the late 1960s and early 1970s the regulations were extended to include other commodities such as oats, barley, sorghum and other grains.

The sampling rate prescribed in the export grain regulation (2.25L / 33 tonnes) was established based primarily on the belt loading speeds of the time (400 tonnes per hour). This rate allowed inspectors five minutes to manually draw a sample, sieve and inspect for insects (Jefferies 2000). The rate was thus established solely on pragmatic considerations rather than being based on a statistical framework to ensure the effective detection of insects (Jeffries 2000).

Hunter and Griffiths (1978) investigate the effectiveness of the Australian export sampling. Using a binomial approach and assuming that insects were homogeneously distributed across the grain mass, they suggested that the approach was effective and could detect insects at very low infestation levels. Hunter and Griffiths (1978) did not test this sampling rate using real data.

The Australian grain sampling rate has been unchanged since it was first established. Sampling throughout the grain storage and supply network has been formulated with the AQIS sampling rate as a guide. Grain growers and grain handlers sample to ensure that grain bulks are insect free to minimise rejections of the consignment at ports or storage facilities. Currently there is a widely held belief that sampling needs to be conducted at or near the rate which AQIS is sampling.

Before this project, no sampling rate in Australia had been tested using real data to determine its effectiveness. Additionally, no sampling programmes currently in use in Australia considered insect spacing and clustering behaviour, fundamental ecological characteristics of these pests that is likely to influence detection. There was an identified need to develop an approach which was testable and based on realistic biological assumptions.

2.5. Identify and prioritise at-risk elements of the supply chain in which improved sampling strategies will maximise efficiency of EPP detection within existing resource constraints

The grain production and supply chain is a complex network in which grain is moved throughout the Australian production region. Grain growers and handlers attempt to minimise the extent of movement from production to storage, however due the isolation of many production areas grain may be shipped up to 1000 km prior to it being exported. Further, storage times on farm, within bulk handling facilities and at ports vary in relation to season and market forces.

Grain is stored in a range of storage types. On farm storages are typically smaller raised silos, however in bulk handling facilities grain may be stored in sheds, large concrete silos or bunkers/pads. Although storages differ significantly no storage is impenetrable to insects. Insects can enter the system at any point, from harvest through to export. As such, all components of the system are at some ‘risk’ of insect infestation. For growers, the first harvest, grain stored for prolonged periods, grain stored in poorly sealed silos or in temporary storages (silo Bags) are at the highest risk. Grain shipments entering and leaving bulk handling facilities however are a primary area of concern for bulk storages. Insects which enter bulk handling facilities may add to control costs and could aid to infest clean storages. Whilst grain leaving storage facilities for export or for local consumption is required to be insect free.

Grain sampling on intake is typically conducted as per Grain Trade Australia guidelines (GTA 2009). These guidelines stipulate that the number of samples to be drawn is directly related to the load size entering the facility.

Table 1: Number of samples for incoming loads as stipulated by Grain Trade Australia (GTA 2009)

GTA rate	Number of Samples
10 tonnes or less	3
10-20 tonnes	4
20-30 tonnes	5
30-40 tonnes	6
40-50 tonnes	7
50-60 tonnes	8
60-70 tonnes	9
70-80 tonnes	10

In contrast, sampling in Western Australia on intake is fixed at four samples per incoming load. It has yet to be determined however if either of these sampling programmes is adequate to detect insects.

On outturn sampling rates vary significantly. Sampling rates vary depending on storage type, transport container (truck or rail car) and storage locality. As such a single fixed set of guidelines to determine best practice sampling has not been developed or investigated.

2.6. Review current leading edge surveillance techniques in closely related fields, including probabilistic and non-probabilistic methodologies

(see Elmouttie et al. A review of current methodologies for in storage sampling and surveillance in the grains industry. *Submitted, Bulletin of Entomological Research)*

Looking beyond the field of stored grain sampling, a range of methodologies have been developed to determine the optimal sampling intensity to detect a target species. Methodologies can be selected on the basis that they provide an adequate statistical description of the spatial distribution of the target species. Typically, sampling methodologies are based on tractable statistical distributions. The binomial, Poisson or negative binomial functions may be appropriate depending on the situation.

Hunter and Griffiths (1978) developed a statistical sampling approach to evaluate the AQIS sampling rate based on the binomial function. The approach was based on the assumption that insects are homogeneously distributed across the grain mass. As such, the method did not need to directly consider sampling intensity but rather overall sample volume, as a sample drawn from any portion of the lot would have the sample probability of detecting insects. In recent years however, it has been well documented that insects are not homogeneously distributed in grain storages. As such, assuming a homogeneous distribution of insects would be invalid.

Alternative methodologies have been developed for sampling stored grain. Unlike the approach developed by Hunter and Griffiths (1978), methods considering insect spacing behaviour have been developed (Hagstrum et al. 1985, Subramanyam et al. 1993, Subramanyam et al. 1997). These approaches which have formed the basis of sampling in the USA, consider sample to sample variation and the number of infested and uninfested samples to determine sampling intensity. Hagstrum et al. (1985) demonstrated that the approach could adequately describe insect a range of insect distributions.

Use of the approach has been limited however, primarily due to its computational complexity and the need for significant amounts of data to parameterise models. Therefore, in the current project it was considered that development of an alternative approach would provide significant benefit to the grains industry.

2.7. Appropriately modify existing sampling methodologies and develop new statistical sampling methodologies as needed that can be appropriately tailored to individual situations

(see Elmouttie et al. 2010. Improving detection probabilities in stored grains*. Pest Management Science.* ***66:*** *1280-1286)*

Insect distributions within stored grains can vary significantly between high and low levels of aggregation and from high to low densities depending on environmental conditions (Rees 2004, Hagstrum and Subramanyam 2006). It is unlikely therefore to find a single, generic probability distribution which adequately represents the range of conditions which may be present in a grain storage and supply network. It is advantageous to develop sampling programmes around a flexible framework that is able to encompass the innate variation that exists within the system. A novel statistical approach to sampling stored grain is presented in Elmouttie *et al.* (2010) and described below. Unlike previous statistical models developed for grain sampling the method presented is based on two distinct probability functions. The model considers that insects may:

a) be heterogeneously distributed throughout grain bulk, and
b) insect densities within grain bulk may be low.

Conceptual Statistical Model – Compound model

The model presented by Elmouttie *et al.* (2010) is based on a two step process, first determining the probability of sampling the infested portion of a grain lot and second determining the probability of returning a positive sample when the sample is drawn from the infested portion of the lot. The implication of this is that not all samples from an infested section of the grain lot will be positive.

An essential assumption of the model is that a grain lot can be separated into two distinct non-contiguous components, an infested portion and a portion free of infestation. Furthermore, it is assumed that the contaminants are homogeneously distributed throughout the infested portion of the consignment, according to the Poisson distribution.

The model identifies the following variables

p = the proportion of the lot which is infested

λ = the rate of contamination per (kg) in the infested part of the lot

n = number of samples drawn from the lot

w = the weight of each sample from (*n*) in kilograms

Let *X* denote the number of samples (from *n*) that originate from the infested portion of the grain lot. Then the number of samples that originate from this infested portion of the lot can be calculated using the binomial distribution $X \sim B(n, p)$ from which follows:

$$P\,(X = x) = \binom{n}{x}\, p^x (1-p)^{n-x}$$

For each sample that comes from the infested part of the lot, the probability of detecting an insect depends on the rate of contamination (λ). Let *A* be the number of insects in the sample conditional on the sample having come from the contaminated part of the lot:

$$P(A = a|X = x) = \frac{e^{-xw\lambda}\,(xw\lambda)^a}{a!}$$

However, of key interest is the situation where no contamination is detected, that is when *a* = 0. In this situation we get:

$$P(A = 0|X = x) = e^{-xw\lambda}$$

Consequently, summing over all possible values for *X* results in the unconditional probability:

$$\begin{aligned} P(A = 0) &= \sum_{i=0}^{n} P(X = i)P(A = 0|X = i) \\ &= \sum_{i=0}^{n} \binom{n}{i} p^i (1-p)^{n-i} e^{-iw\lambda} \\ &= \sum_{i=0}^{n} \binom{n}{i} \left(pe^{-w\lambda}\right)^i (1-p)^{n-1} \\ &= \left(1 - p + pe^{-w\lambda}\right)^n \end{aligned}$$

The final step in the equation is derived from the Binomial theorem:

$$(a+b)^n = \sum_{i=0}^{n} a^i b^{n-i}$$

Therefore the probability of detection is given:

$$P(A > 0) = 1 - P(A = 0)$$

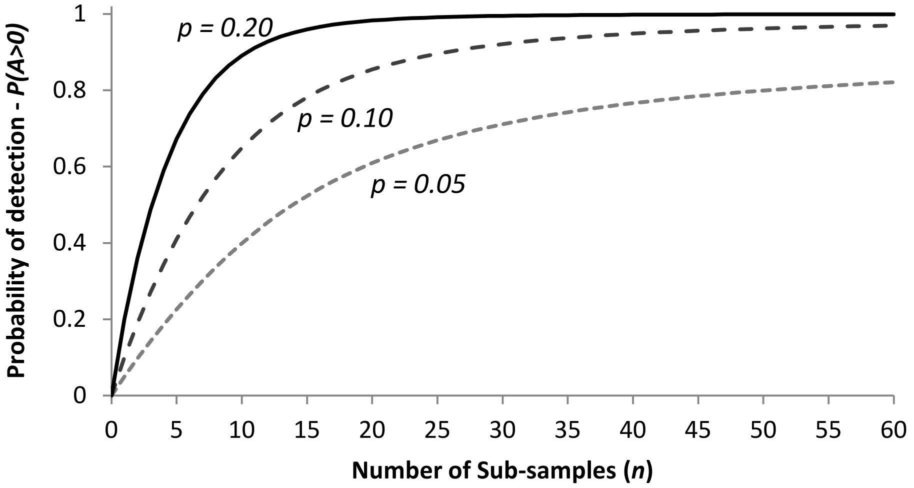
$$= 1 - \left(1 - p + pe^{-w\lambda}\right)^n \text{ (Compound model)}$$

The model is dependent upon four distinct parameters which influence the probability of detection. To date these model parameters have been based on limited empirical data and simulated data. It is therefore important that robust parameter estimates are developed to maximise the effectiveness of the model.

Model behaviour – Compound model

The model presented above considers that both the rate of infestation (λ) and the proportion of the lot infested (p) will influence detection in bulk grain lots. However, although λ and p affect the probability of detection of insects within grain lots when a grain lot is sampled, these will be unknown quantities. The number of sub-samples n and the sample weight w can be varied however, and so variations in these parameters form the basis for sampling strategies. We consider here the influence of sub-sampling on the probability of detection of insects under various combinations of λ and p.

a)



b)

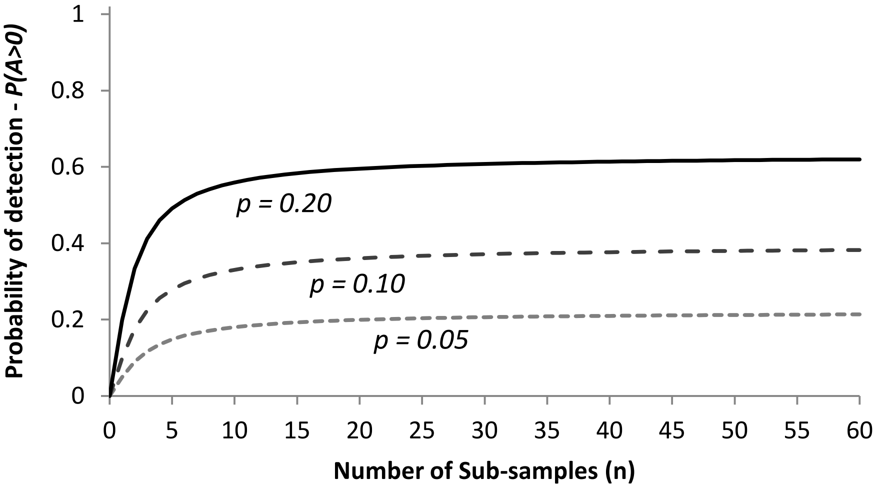
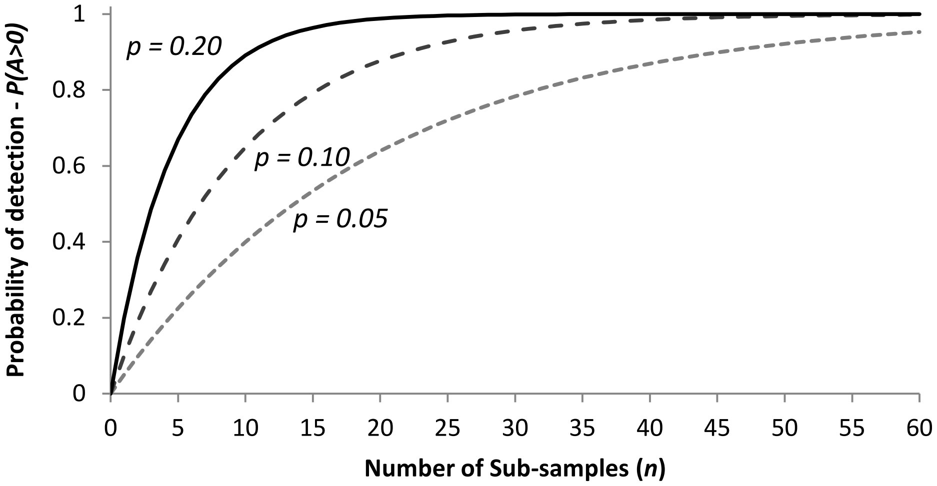


Figure 1a & b: The probability of detecting insects in a grain lot, in relation to the number of sub-samples drawn for various levels of heterogeneity, *p*. a) *nw* is held at a constant 10 kg with λ = 5 and b) For the example presented here, *nw* is held at a constant 10 kg with λ = 0.5.

The figures above illustrate the effects of changes in sub-sampling on the probability of detecting insects for high (λ = 5) and low (λ = 0.5) infestation rates at a fixed sample weight (*nw* = 10kg), representing the most intensive sampling rate recommended by Grain Trade Australia (2009). Here, the probability of detecting an insect increases as the number of sub-samples increases although the overall sample weight (*nw*) is constant. The level of increase will vary according to the underlying infestation rate (Figures 1a and 1b). Below we illustrate the effect when sample weight is not constant.

a)



b)

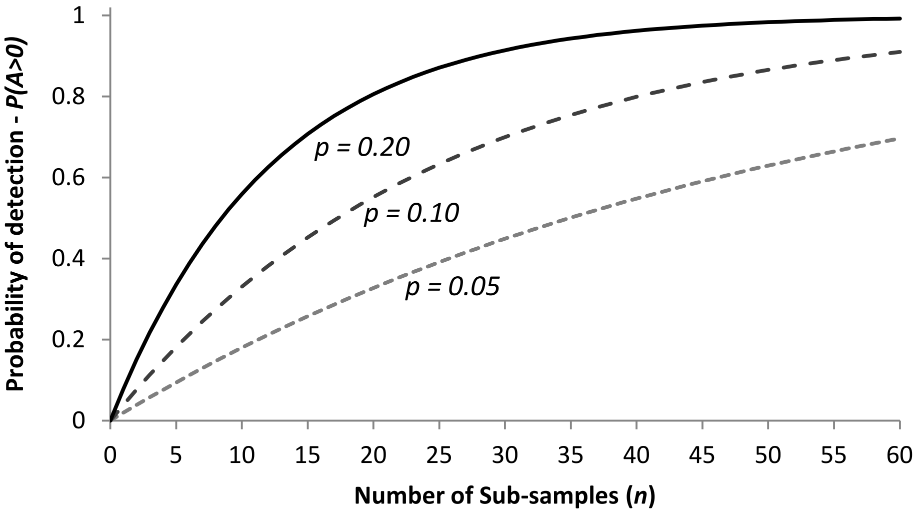


Figure 2a & b: The probability of detecting insects in a grain lot, in relation to the number of sub-samples drawn for various levels of heterogeneity, *p* were a) *w* is held at a constant 1 kg and $\lambda = 5$ and b) *w* is held at a constant 1 kg and $\lambda = 0.5$.

In figures 2a and b, illustrate the probability of detecting an insect increases as the total sample weight increases (shown here by increasing the number of sub-samples with a fixed sub-sample weight). The rate of increase in the probability of detection is also significantly higher when the total sample weight increases in comparison to when *nw* remains constant (Figures 1a & 2a; 1b & 2b). In all examples the detection curve asymptote is reached significantly quicker as *p* increases, leading to fewer sub-samples being required for increased detectability.

2.8. Assess the accuracy of methods used to detect pest species

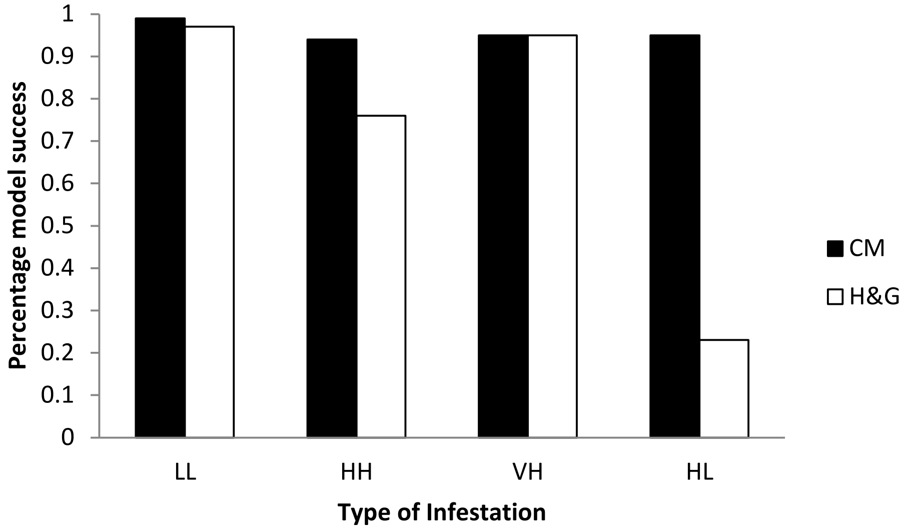
A comparison of Hunter and Griffiths (1978)

Hunter and Griffiths (1978) developed an approach based on mean insect density and sample volume from a known sized grain bulk to determine the effectiveness of the AQIS sampling plan. The approach was developed assuming a homogenous distribution of insects rather than considering the fact that insects tend to be patchily distributed through the grain bulk.

Conversely, the approach developed in this project (Compound model) differs as it considers insect biology and behaviour. The approach accounts for the fact that insect may be patchily distributed throughout the grain bulk with some areas not containing insects and other with insects at some density. The approach also considers the effect of both sampling intensity and sample size on detection rather than be based solely on the overall sample volume.

Figure 3a & b compare the rate of detection of the Hunter and Griffiths (1978) model to the Compound model using real data. Data was collected from grain storages that were intensively sampled to determine mean insect density. Data from various time periods were used to make sampling predictions for each model at a 95% probability of detection. A range of data types and distributions were investigated to determine under what conditions each model performed the best. The model predictions were then used to sample data repeatedly (10,000 times) in a Monte Carlo simulation. This was then used to determine the percentage success rate of each model.

a)



b)

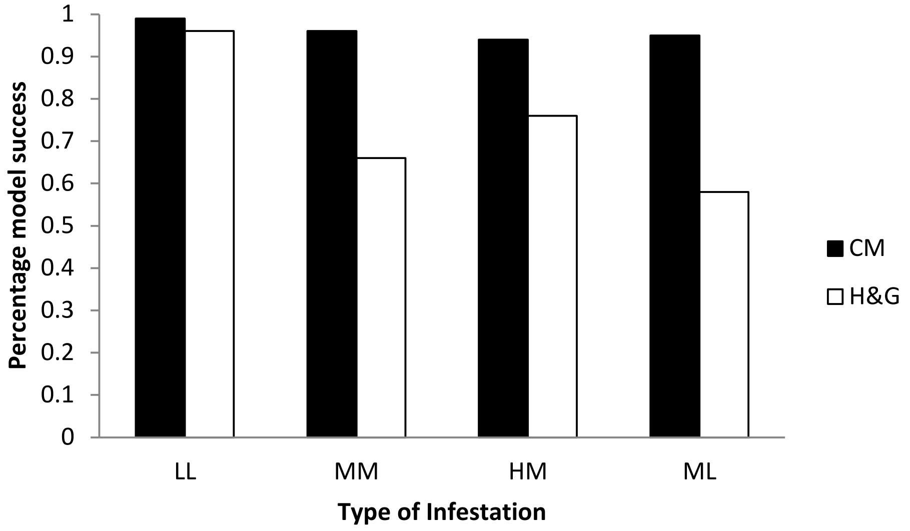


Figure 3a & b: Percentage model detection rate success for the Compound model and the model developed by Hunter and Griffiths (1978) sampling (a) *Rhyzopertha dominica* and (b) *Cryptolestes ferrugineus.* The type of infestation refers to the density of insects and the proportion of the grain mass which they are found during the time of sampling. LL – Low density infestation and low proportion infested (less than 0.20 insect per kg & < 25% proportion infested), ML – Moderate insect density and low infestation (0.2-3 insect per kg & less than

25% lot infestation), MM – Moderate insect density and moderate proportion infested (0.2-3 insects per kg & 25-50% proportion infested), HL – High density infestation and low proportion infested (3 – 25 insects per kg & less than 25% infested), HM – High density infestation and moderate proportion infested (3 – 25 insects per kg and 25-50% infested), HH – High density of insects and high proportion infested (3 – 25 insects per kg & greater than 50% infested) and VH Very High infestation (greater than 25 insects per kg & greater than 75% infested).

Figure 3 illustrates that, irrespective of insect density or proportion of grain infested, the Compound model performs well and detects insects at the desired 95% detection rate. In contrast, detection rates using the Hunter and Griffiths (1978) approach fail to detect insects across all infestation types. When insect density is very low (< 0.2 insect per kg), both models perform well and have the same detection rate. In this scenario because the overall density of insects in the lot is low, consideration of insect spacing behaviour is not relevant. Both models perform well where insect density is very high. This is unsurprising since very few samples would be sufficient to detect insects when they are at an unrealistically high level throughout the lot.

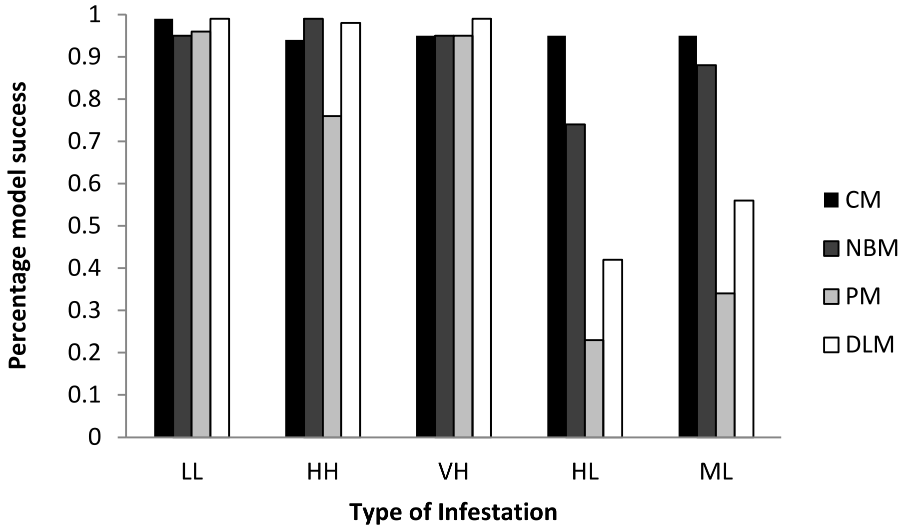
Of particular importance however is the failure of the Hunter and Griffiths (1978) model when insect density is locally high but restricted to a confined area. The Compound model performed between 20-400% more efficiently than the Hunter and Griffiths approach when insects were patchily distributed within grain lots. This is an important development as these types of infestation are common in storages, particularly where infestation is a result of a local microclimatic factor (e.g. moisture from in confined area of storage) or due to a confined harbourage area in the storage (e.g. area where fumigant does not penetrate) or an area which allows access to immigrating pests (breakage in storage seal).

Comparison of the Compound model to alternative sampling approaches

(See Elmouttie et al. Sampling stored product insect pests: a comparison of statistical sampling models to maximise pest detection- *Submitted, Pest management Science).*

A number of sampling models have been adapted for sampling biological systems. Poison models have typically been used to sample targets which are rare in the sample area however have also been considered as a good model to approximate aggregation. Negative binomial models are also commonly used to approximate species aggregation. Here we compare the rate of detection of four models, negative binomial (NBM), Poisson Model (PM) the Compound model (CM) and a model developed specifically for grain sampling by Hagstrum et al. (1985) (denoted here as the DLM – Double log model). Using the same Monte Carlo method for comparison as conducted with the Hunter and Griffiths model we investigate model detection over a range of data types for two common pest species at a 95% level of detection.

a)



b)

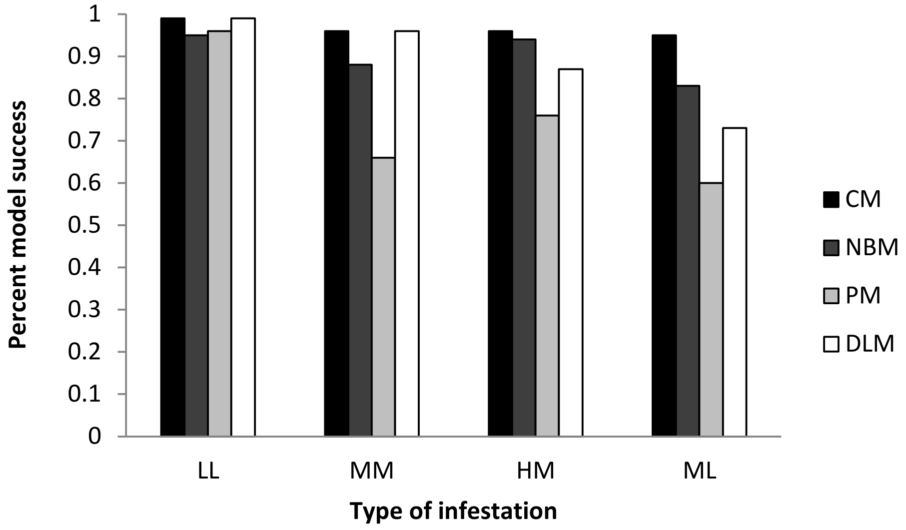


Figure 4a & b: Percentage model detection rate success for the for tested models for (a) *Rhyzopertha dominica* and (b) *Cryptolestes ferrugineus.* The type of infestation refers to the density of insects and the proportion of the grain mass which they are found during the time of sampling. LL – Low density infestation and low proportion infested (less than 0.20 insect per kg & less than 25% proportion infested), ML – Moderate insect density and low infestation (0.2-3 insect per kg & less than 25% lot infestation), MM – Moderate insect density and moderate proportion infested (0.2-3 insects per kg & 25-50% proportion infested), HM – High density infestation and moderate proportion infested (3 – 25 insects per kg and 25-50% infested).

Similarly to figure 3a & b, figure 4a & b illustrates that the Compound model performs well across a range of insect densities and proportion of grain infested. Of the four models examined the Poisson model performed worst consistently falling below the desired 95% detection rate and similarly to the Hunter and Griffiths approach only performing well when insect density is high or very low. Both the DLM and NBM performed better than the Poisson approach however failed to detect at the 95% confidence range when insect distribution were clustered at high density, i.e. local distributions.

2.9. Review current leading edge surveillance techniques in closely related fields, including probabilistic and non-probabilistic methodologies & Identify a range of information resources that can be merged with existing or newly developed sampling methods to increase the power of analyses and provide evidence of freedom from specific EPPs

(see Elmouttie et al. A review of current methodologies for in storage sampling and surveillance in the grains industry. *Submitted, Bulletin of Entomological Research)*

Effective sampling and surveillance strategies form an integral component of large agricultural industries such as the grains industry. Intensive sampling is essential for pest detection, integrated pest management (IPM) and to satisfy biosecurity concerns within shipments, while surveillance over broad geographic regions ensures that biosecurity risks can be excluded, monitored, eradicated or contained. In the grains industry, a number of qualitative and quantitative methodologies for surveillance and in storage sampling have been considered. Primarily, the research has focussed on sampling strategies concentrating on ‘within silo’ detection, however the need for effective surveillance strategies has been recognised. Interestingly, although surveillance and in storage sampling has typically been considered independently, the two fields have many techniques and concepts in common.

Quantitative sampling methodologies based on statistical probability functions and detection surveys have typically been used in sampling approaches, whilst in surveillance a greater range of methodologies have been considered. Qualitative approaches have been considered for surveillance such as fault trees, stakeholder questionnaires, expert opinion and critical examination. Many of these methods have also been incorporated with more robust quantitative methods such as detection surveys, scenario tree, stochastic modelling and Bayesian approaches.

Although often developed in isolation methodologies used in broad scale surveillance and in storage sampling are similar in concept (e.g. detection methods), however techniques have rarely crossed disciplines. In an industry as large as the grain industry, which involves the production, storage and export of grain over large geographic areas and issues of area freedom, broad scale surveillance and in storage sampling, there are advantages in exploring alternative multidisciplinary techniques to achieve these goals across the industry.

In storage sampling and surveillance techniques have been developed independently, largely in response to specific issues facing the grain industry at a given time. For example, in storage sampling techniques primarily arose as a response to poor hygiene in storages, to secure trade routes. Methodological development was *ad hoc* and based on practical restrictions. Newer sampling methodologies for use in grain storages have been developed primarily for IPM purposes (Hagstrum et al. 1985, Lippert and Hagstrum 1987, Subramanyam et al. 1997) and although statistically robust, methods are not focused on detection but rather on mean abundance estimation and as such have limited suitability for surveillance.

Surveillance methods for biosecurity in contrast are relatively new concept for the grains industry (Taylor and Slattery 2008). A number of methodologies developed for surveillance however may also have application for in storage sampling programmes in the grains industry. For example, stochastic scenario trees have been used extensively in surveillance but may also help in the development of cost effective in storage sampling systems.

Bayesian methods may provide the most significant improvements to the grains surveillance and in storage sampling systems. The most significant advantage of such methods is the capacity to utilise multiple forms of data (e.g. expert opinion, prior knowledge) in a single analysis. For example, Bayesian belief networks have been used to incorporate a range of data sources for the prediction of algal blooms (Hamilton *et al.* 2007), and fish and wildlife viability (Marcot *et al.* 2001). These studies illustrated the utility of these approaches as predictive tools where multiple data types are present. As such, Bayesian analysis provides a methodology to incorporate multiple forms of both surveillance and sampling data to improve predictive power and inform sampling models (Marcot et al. 2001). Across the grain industry, a range of data (qualitative and quantitative) is collected for surveillance purposes and pest management by government agencies, local land owners, industry professionals and research. Although the data is of value, it is often not utilised to its full potential, as data collection methods vary from region to region and between land owners, industry groups etc. As such, analysis for any one surveillance or sampling activity only uses a portion of the total available data. Similar to scenario trees, Bayesian techniques may also provide a means to incorporate alternative data types to inform parameter estimates of alternative sampling and surveillance approaches.

The statistical method developed in this project is similar to surveillance methodologies as it considers that both the prevalence and intensity of individuals within an area has an influence on the probability of detection. As such, the approach may be used to tie surveillance and in storage sampling systems together. Further, the methodology proposed contains two parameters which need direct estimation, the prevalence of pests and their intensity. As these parameters are a direct translation of a biological occurrence they may be estimated from a number of data sources. As such a Bayesian approach to incorporate multiple data forms with uncertainty may provide a valuable tool for sampling models for in storage sampling and surveillance systems.

2.10. *Development of a sampling methodology for use in Integrated Pest Management (IPM)*

(See Elmouttie et al – Sampling grain to a compliance threshold: implications for Integrated Pest Management – *Submitted, Journal of Stored Product Research)*

Sampling methodologies for IPM are designed to detect pest species at a given target or treatment threshold. We extend the Compound model to consider alternative compliance thresholds. The addition of alternative compliance thresholds increases the capacity of a sampling programme to detect target pests at a treatment threshold when compared to a zero tolerance approach and thus has important implications for IPM.

The model-IPM

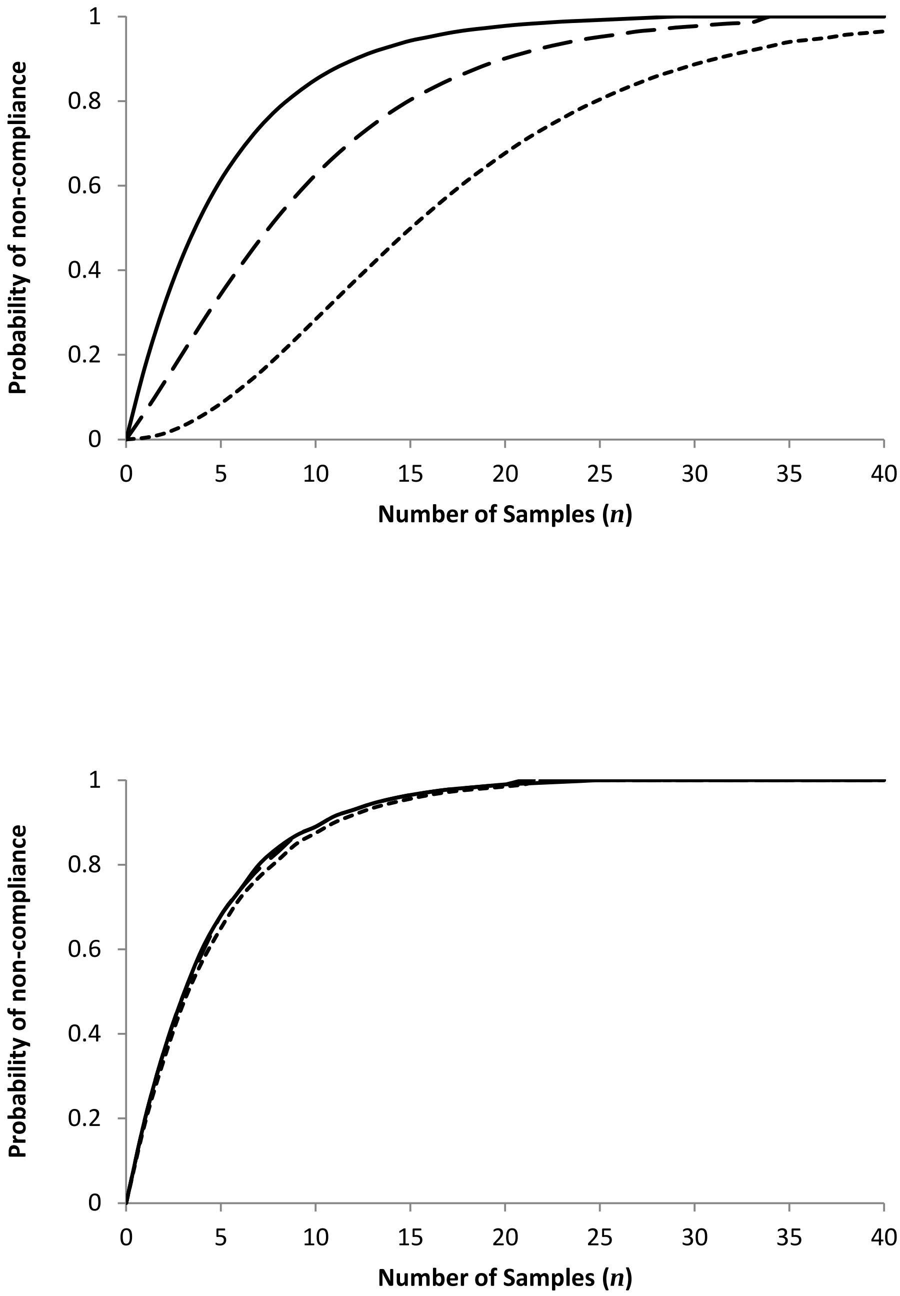
When developing IPM strategies, detection at alternative compliance thresholds may be of interest, that is when $a > 0$. Non-compliance is then given when the number of insects throughout the grain sampled exceeds the compliance threshold, a. In this case it can be shown that the probability of non-compliance is given by:

$$P(A > a) = 1 - \sum_{j=0}^{a} \sum_{i=0}^{n} P(X = i) P(A = j | X = i)$$

$$= 1 - \textstyle\sum_{j=0}^{a} \sum_{i=0}^{n} \binom{n}{i} p^{i} (1-p)^{n-i} \frac{e^{-iw\lambda} (iw\lambda)^{j}}{j!}$$

The effect of three arbitrary compliance thresholds (0, 2, and 5) on the sampling intensity required to achieve a probability of non-compliance of 0.95 was examined. As no treatment threshold has been developed for Australia we base our analysis on the threshold used in the USA. As such, estimates for insect density (λ) in the infested portion of the lot are set at 2 and 10 per kg, whilst initially we consider a scenario where $p = 0.2$, that is, 20% of the lot is infested. Note that an infestation of 10 insect per kilogram ($\lambda = 10$) over 20% of the lot equivalent to 2 insect per kilogram over the entire lot which represents the threshold for treatment in the USA.

a)



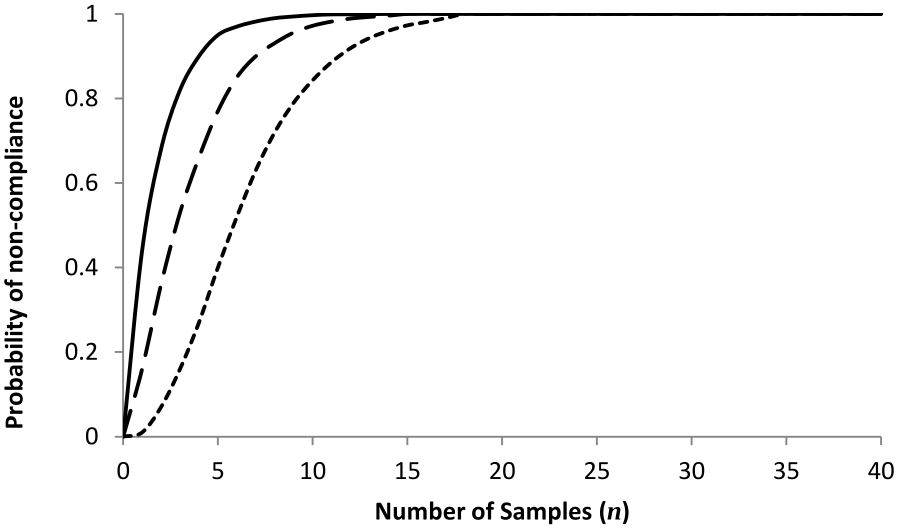
b)

Figure 5a & b: The probability of non-compliance at three alternative compliance thresholds ($a = 0$, $a = 2$, $a = 5$) when (a) insect density $\lambda = 2$ and (b) insect density $\lambda = 10$. The weight of samples is held constant ($w = 1$kg) as is the proportion of the lot infested ($p = 0.2$). ($a = 0$ ––, $a = 2$ — —, $a = 5$ - - -)

Figure 5 illustrates that a greater number of samples are required for a higher probability of non-compliance irrespective of the compliance thresholds. When the density of insects is low however ($\lambda = 2$), determining non-compliance at higher thresholds requires substantially more samples to be drawn (figure 5a). In contrast, when the density of insects is high ($\lambda = 10$) the number of samples required to determine non-compliance is equivalent for all thresholds considered here (figure 5b). This occurs because at high densities a 1kg sample is almost guaranteed to contain more insects than the largest threshold considered, provided the sample is drawn from a contaminated part of the lot. In contrast at lower densities this is not the case.

In this example the proportion of the lot infested remained constant ($p = 0.2$). However, the proportion of the lot infested p, also influences the probability of non-compliance at alternative thresholds. We now consider the probability of non-compliance in a situation where the infestation is more widespread in the grain bulk, where $p = 0.5$ and infestation rates in that part of the lot are again $\lambda = 2$ and $\lambda = 10$ (Figure 6a and b).

a)



b)

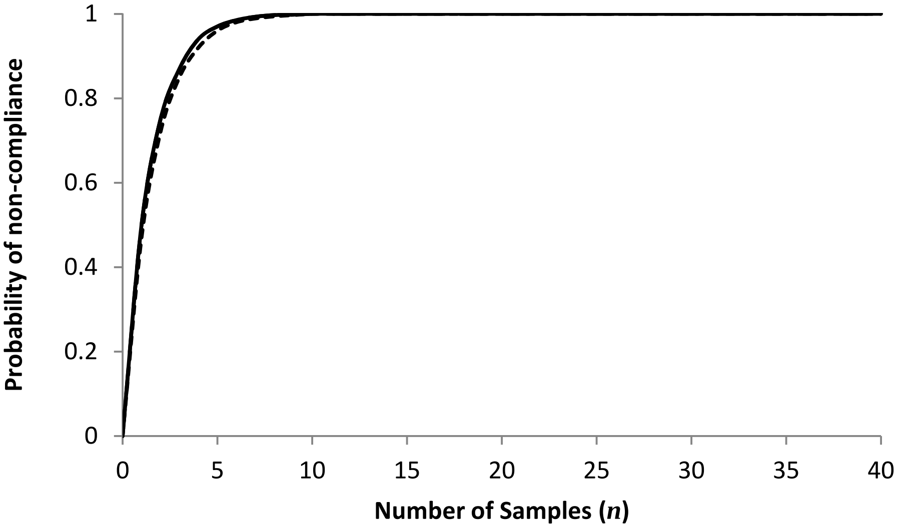


Figure 6a & b: The probability of non-compliance at three alternative compliance thresholds ($a = 0$, $a = 2$, $a = 5$) when (a) insect density $\lambda = 2$ and (b) insect density $\lambda = 10$. The weight of samples is held constant ($w = 1$) and the proportion of the lot infested also is held constant ($p = 0.5$). ($a = 0$ ---, $a = 2$ ——, $a = 5$ - - -)

When insect density is low ($\lambda = 2$) the number of samples required to reach a given probability of non-compliance increases as the compliance thresholds increases (figure 6a). However, similar to the first example, when the density of insects in the lot is high ($\lambda = 10$) the number of samples required to achieve a given probability of non-compliance is equivalent across all thresholds. When a zero tolerance threshold is set, the number of samples required to determine non-compliance at high and low densities of insects within the infested portion of the lot is also equivalent, that is, when insect density is above 2 sampling intensity is equivalent at the zero tolerance threshold (Figures 1 a and b, Figure 6 a and b). This response is directly related to the density of the infestation examined here. If the density in the infested portion of the lot was lower than the value used here ($\lambda = 2$), these observations would not hold. Elmouttie *et al.* (2010) demonstrated that sampling intensity was different for a zero tolerance threshold when a $\lambda = 0.5$ was compared to a $\lambda = 5$. Compliance thresholds therefore provide a mechanism to discriminate between treatment thresholds based on both the density of the infestation (λ) and the proportion of the lot infested (p) (Figures 5 a and b, Figure 6 a and b). As demonstrated, if a threshold of $a = 0$ is set, it is not possible to differentiate if insect density within the infested portion of the lot is two ($\lambda = 2$) or greater as an increase in λ does not result in more samples being required (Figures 5a & b, Figure 6a & b). This lack of discrimination occurs because at a threshold of $a = 0$, a non-compliance is recorded whenever one or more insects are found within a sample. That is, additional insects are not accounted for. In the examples provided, sampling at a threshold of $a = 5$ when the density in the infested portion of the lot is high ($\lambda = 10$) does not require more samples to be taken to determine non-compliance at a given probability (e.g. 0.95) than the other thresholds examined. However, when the density in the infested portion of the lot is low, more samples are required to achieve the equivalent probability of non-compliance for higher thresholds. As the density of insects within the infested portion of the lot increases, the probability that samples will contain multiple insects also increases. However, as the density in the infested portion of the lot decreases there is a corresponding decrease in the probability of samples containing multiple insects. As such, compliance thresholds provide end-users a method to ensure that the proportion of the lot infested and the density within that infested portion corresponds to the pre-determined treatment threshold.

Sampling and Treatment costs

A key factor that will drive decision making along the grain supply chain is the costs or savings that will result from changed management practices. Here we consider the costs of sampling and treatment at an arbitrary action threshold basing results on current Australian practices and costs. As economic treatment thresholds have not yet been determined for Australian storages we consider a scenario where treatment (fumigation) is required when 20% of the grain is infested ($p = 0.2$) and a mean density of insects in infested portions equal 10 or more ($\lambda = 10$). As shown in Elmouttie *et al.* (2010), these parameters are realistic for Australian conditions. This also equates to 2 insects per kilo (as per the USA treatment threshold) (Hagstrum *et al.* 1999). A compliance threshold of a = 5 is selected as this provides the greatest certainty that the density of insects within the infested portion of the lot is equal to or greater than 10 at a specified confidence level however does not result in added sampling effort. This is illustrated in figure 1b where sampling intensity (number of samples to be drawn) is no different between a = 0, a = 2 or a = 5 when λ = 10 for the equivalent probability of non-compliance. Determining non-compliance at these parameters would require at least five insects to be found in 15 x 1kg samples for a 95% probability of non-compliance (Figure 1b).

Table 2: Costs associated with fumigation and sampling under three sampling scenarios, a) calendar based fumigation with no sampling, b) sampling one month after fumigation and fumigation at non-compliance, and c) sampling two months after fumigation and fumigation at non-compliance and three temperatures (22°C, 27°C and 32°C) with constant grain moisture (11.5%). Fumigation costs are based on industry estimates for labour associated with application of Vaporphos at 1 gram per tonne for a 20,000 tonne bunker, plus bunker clearance and monitoring costs. Sampling costs are based on four hours labour at current rates ($ 50AUD/ hour). (Sam = Sampling conducted, Treat = Treatment, N = No action taken, S = Samples taken, D = compliance at threshold *a* = 5 , F = Fumigation)

				Temperature 22°C						Temperature 27°C						Temperature 32°C					
	Scenario 1			Scenario 2			Scenario 3			Scenario 2			Scenario 3			Scenario 2			Scenario 3		
Month	Sam	Treat	Cost	Sam	Treat	Cost	Sam	Treat	Cost	Sam	Treat	Cost	Sam	Treat	Cost	Sam	Treat	Cost	Sam	Treat	Cost
1	N	N		N	N	-	N	N	-	N	N	-	N	N	-	N	N	-	N	N	-
2	N	N		S	N	200	N	N	-	S	N	200	N	N	-	S	N	200	N	N	-
3	N	F	3800	S	N	200	S	N	200	S	N	200	S	N	200	SD	Y	4000	SD	Y	4000
4	N	N		S	N	200	S	N	200	SD	F	4000	SD	F	4000	N	N	-	N	N	-
5	N	N		SD	F	4000	SD	F	4000	N	N	-	N	N	-	S	N	200	N	N	-
6	N	F	3800	N	N	-	N	N	-	S	N	200	N	N	-	SD	Y	4000	SD	Y	4000
7	N	N		S	N	200	N	N	-	S	N	200	S	N	200	N	N	-	N	N	-
8	N	N		S	N	200	S	N	200	SD	F	4000	SD	F	4000	S	N	200	N	N	-
9	N	F	3800	S	N	200	S	N	200	N	N	-	N	N	-	SD	Y	4000	SD	Y	4000
10	N	N		SD	F	4000	SD	Y	4000	S	N	200	N	N	-	N	N	-	N	N	-
11	N	N		N	N	-	N	N	-	S	N	200	S	N	200	S	N	200	N	N	-
12	N	F	3800	N	N	-	N	N	-	SD	F	4000	SD	F	4000	Y	Y	4000	SD	Y	4000
Total			15200			9200			8800			13200			12600			16800			16000

Results from the cost analysis presented in Table 2 are based on Australian industry phosphine fumigation rates and include application, product clearance and labour charges, totalling $3800/20000 tonne bunker. The cost analysis illustrates that even when the time required to take samples is unrealistically high leading to inflated costs ($200 =$50 per hour for four hours to collect 15 samples) if less than four fumigation treatments are used a substantial cost saving can be achieved. In fact, Scenarios 2 and 3 at both 22°C and 27°C illustrate that one to two fumigations annually can be prevented, resulting in cost savings of approximately 40% and 17% respectively, even if sampling is conducted over nine months of the year. At higher temperatures (e.g. 32°C), no savings are demonstrated using the comparison presented. However growth estimates presented here are a worst case (i.e. rapid growth due to high temperatures and humidity) scenario and do not consider the effect of insect mortality, alternative treatments and seasonal climatic variation, for which we have no current data. Further, sampling also provides data relating to commodity damage and quality and the effectiveness of treatments, all of which have not been quantified here.

2.11. Incorporate imperfect detection into sampling plans

In recent years it has been well documented, that for a number of species detectability is less than one when conducting field surveys (Mackenzie *et al.* 2002). A detectability estimate of below one, suggests that even species within a sample or sampled area may not be detected. However methodologies developed for grain storages assume perfect detection of insect pests within an examined sample. This is unlikely to be true as individual species behavioural and feeding characteristics will influence if insects are detected within a sample. For example, *Rhyzopertha dominica* (Lesser Grain Borer) will bore into a grain kernel to feed (Rees 2004). As such, if an individual is within a grain kernel when a sample is drawn and sieved it is unlikely to be detected. Sampling methodologies should therefore be designed considering detectability as failing to do so may lead bias predictions of insect density.

By extending the original model developed by Elmouttie et al. (2010) we demonstrate that detectability estimates can be included into grain sampling programmes. Using real data and simulation experiments we illustrate that detectability estimates can be calculated and included into sampling approaches. Our research demonstrates that the inclusion of detectability estimates increases the detection rates significantly (Figure 7).

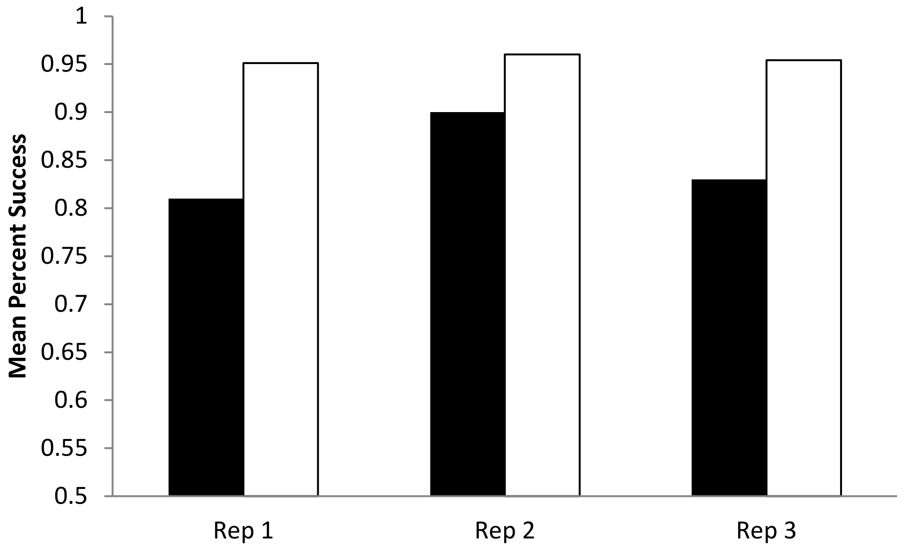


Figure 7: Mean percent simulation success with and without detectability estimates considered. (■ detectability = 1, □ detectability estimated)

Figure 7 illustrates that assuming detectability to be equal to one can reduce true detection rates significantly. Detectability estimates will vary in relation to a number of factors, however where possible they should be included to maximise detection rates. Imperfect detection can be overcome using a number of methods including longer inspections and infra-red technologies to detect pest. Inclusion of detectability will not aid in the detection of eggs or larvae however, as these stages cannot be detected easily. Unlike alternative methods to deal with imperfect detection (e.g. infra-red and x-ray) incorporation of detectability estimates into sampling methodologies is not costly, as only an increased sampling effort needs to be considered when detectability is low.

3. Implications for stakeholders

Effective sampling strategies need to be developed based on a robust statistical framework which accounts for insect biology and behaviour. The model developed in this project is the first to consider insect biology and account for the spatial variation of insects within grain bulks in a form which is easy to compute.

This approach provides stakeholders a simple tool which can be used to determine the effectiveness of current sampling methodologies. Furthermore the model also provides stakeholders a methodology to develop new sampling programmes based on robust statistics.

The relevance of model parameters allows estimation to be conducted using a number of techniques. Although developing robust parameter estimates for specific regions using intensive sampling data is favourable, end users and stakeholders could estimate parameters using existing data or expert opinion.

The model also allows grain growers and grain handlers to develop sampling programmes based on an acceptable level of risk insect density of given size. Previously this has been difficult to ascertain in models which consider clustering behaviour due to their complexity.

This approach allows stakeholders to optimise sampling programmes by considering both the number of samples and their size. This data will provide significant benefits particularly when acquiring new or updating current sampling equipment.

The extension of the model to include alternative compliance thresholds allows, for the first time, sampling specific to integrated pest management to be developed in Australia. This not only provides stakeholders a means to more efficiently utilise controls but also to manage issues relating to fumigant resistance in pest species.

4. Recommendations

- Sampling methodologies should be modified to maximise detection at a given pest density rather than not solely attempting to replicate the AQIS sampling plans for a given volume.
- It is preferable to use sampling models that explicitly consider insect clustering behaviour to give the most accurate detection estimates.
- Grain growers and grain handlers should consider having various sampling programmes for various objectives – for example detection programmes for zero tolerance sampling, versus alternative thresholds as part of an IPM system.
- Sampling should be based on maximising detection at a given tolerance level.

4.1. Sampling intensity

Sampling of bulk grains in Australia is typically determined by the size of the storage or shipment being sampled. The methodology developed in this project suggests that a fixed number of samples may provide a more effective and efficient sampling method regardless of the volume of the commodity being sampled.

For example, Grain Trade Australia (2009) have various recommended sampling rates in relation to incoming truck sizes to bulk handling facilities (Table 3). Results from these studies suggest that drawing between 6-7 from all shipments would be more efficient than having a sampling rate that varies in relation to load size (Table 3).

Table 3: Probability of detection in relation to GTA Sample number for an insect infestation occupying 25% of shipment and at a density of 2 insects/kilogram.

GTA rate	Number of Samples	Probability of Detection (%)
	1	21.6
	2	38.6
10 tonnes or less	3	51.8
10-20 tonnes	4	62.2
20-30 tonnes	5	70.4
30-40 tonnes	**6**	76.8
40-50 tonnes	**7**	81.8
50-60 tonnes	8	85.7
60 -70 tonnes	9	89.8
70-80 tonnes	10	91.2
	11	93.1
	12	94.7

Table 3 illustrates that drawing between 6-7 samples would provide a high level of detection, approximately 80%. Modifying sampling intensity in relation to load size does increase the rate of detection for large loads however, for smaller loads, sampling is insufficient to detect pests with a level of confidence 75%.

When grain is leaving bulk facilities for export grain handlers attempt to ensure that grain that is pest free, and this is supported by sampling. Grain for export however is sampled by AQIS at a rate of 2.25 litres per 33 tonnes of grain. This is an intensive sampling programme with more samples drawn as the volume of grain for export increases. Table 4, provides examples of the sampling intensity that AQIS undertakes in relation to grain bulk volume.

Table 4: Number of samples drawn at AQIS sampling rate (2.25L/33t) in relation to grain bulk volume.

Load Size (tonnes)	Number of Samples
5,000	151
10,000	303
20,000	606
30,000	909
40,000	1212
50,000	1515

Meeting sampling rates that AQIS performs are likely to be prohibitive for large grain bulks due to cost and time limitations associated with sampling.

Therefore, it is important to determine what sampling intensity is necessary to maximise detection under an assumption that insects may be present at some density in the bulk. The statistical approach developed in this project is unlike previously developed approaches as it explicitly considers the proportion of the grain which is infested with insects and the density of insects (insects/kg) within that infested portion of grain. Sampling rates need not vary in relation to the size of the bulk being transported but rather the density of insects in the infested portion of the grain. Table 5 illustrates proposed sample rates for varying combinations of contamination proportion and insect density at three differing rates of detection. For consistency sample size is fixed at 1.6kg which represents the AQIS sample rate for wheat (2.25L of wheat = 1.6 kg). It should be noted if the sample volume was smaller, the number of samples required for detection would differ.

Table 5: Probability of detection for various sampling intensities in relation to the proportion of the grain within a grain lot which is infested and density of insects within that infested portion.

		Proportion of grain infested %		
Number of samples	Density of infestation/kg	1	2	5
25	1	18	33	63
50	1	33	55	86
75	1	45	70	95
100	1	55	80	98
150	1	69	91	99
200	1	79	96	99.9
250	1	86	98	100
300	1	91	99	100
350	1	95	99	100
25	5	22	39	72
50	5	40	63	93
75	5	52	78	98
100	5	63	86	99
150	5	77	95	99.9
200	5	86	98	100
250	5	91	99	100
300	5	95	99.7	100
350	5	97	99.9	100

Table 5 illustrates that sampling rate is effected by both the density of insects in the infested portion of the bulk and the proportion of the grain which is infested. This occurs irrespective of the size of the grain bulk as the average density of insects over the entire bulk would remain constant for any given insect density and proportion of grain infested combination. Table 6 illustrates the average insect density within a grain bulk relative to the above combination of insect density and proportion of infestation.

Table 6: Average number of insects per kilogram over an entire grain bulk for various combinations of the proportion of the grain infested and the density of the infestation within the infested portion.

	Proportion of grain infested %			
Density of infestation/kg	1	2	5	10
1	0.01	0.02	0.05	0.10
2	0.02	0.04	0.10	0.20
5	0.05	0.10	0.25	0.50
10	0.10	0.20	0.50	1.00

Clearly average insect density will vary in relation to the proportion of the grain infested and the density of insects in the infested portion of the grain (Table 6). However a comparison of table 5 and 6 illustrates that sampling intensity is not directly related to average insect density. In fact, for the equivalent average insect density different sampling intensities can be achieved, which relate to the proportion of grain infested and the density of infestation. When large sample volumes are drawn however, as is the case with grain sampling, the proportion of the grain infested has the most significant influence on detection rates (Table 5). As such, the risk of not sampling an infestation should be determined primarily by considering how much of the grain may be infested and secondly the insect density. Potential areas of insect immigration, time since fumigation, any breaks in storage seals and imperfect fumigation will all influence the proportion of the grain that is infested. However, Table 5 provides sampling guidelines for grain bulks and illustrates that a high level of detection (0.95) can be achieved for small infestation restricted to small areas of the bulk with significantly less sampling than is conducted by AQIS.

4.2. *Point Recommendations sample intensity*

- Sampling strategies should be based on a fixed number of samples irrespective of bulk size.
- An intake drawing six to seven samples will provide detection of moderate infestations with a probability of 80%.
- In storage sampling at between 50-75 samples per storage will allow for detection of infestations which are present in less than 5% of grain lot.

4.3. *Sample size and sample number*

Sampling programmes in the bulk grains industry have been typically developed based on grain bulk size and sample fraction that is drawn from a specific bulk. As such, no consideration between the influences of sample number versus samples size is considered as the overall sample fraction dictates the probability of detection. This project has illustrated that both the number of samples and the size of the samples drawn will influence the probability of detection in a given bulk. The influence of sample size over sample volume is driven by the density of insects within the grain bulk. Table 7 illustrates the effect of sample size and volume of detection rates.

Table 7: The number of samples required for sample sizes (*w*) of 1kg, 2kg and 3kg in relation to the proportion of grain infested with insects

	Sample size (w) in kg		
Percentage of grain infested	1	2	3
5	94	67	61
10	46	33	30
20	22	16	14

Table 7 illustrates that drawing multiple small samples reduces the overall volume which is required to be inspected, particularly when lot infestation rates are low. Given that insect densities less the 2 insect per kilo (within the infested portion of the lot) are difficult detect, and lot infestation is commonly less that 20% greater number of smaller samples would provide a higher level of detection.

4.4. Point Recommendations Sample size and sample number

- In general, drawing multiple small samples will provide increase detection rates while reducing the total volume of grain sampled.
- When target density is very low (< 1 insect /kg) sample volume should be increased to maximise detection.

4.5. Point Recommendation IPM

- The introduction of IPM sampling strategies in Australia based on a compliance threshold would aid in phosphine resistance management and reduce costs.
- An appropriate thresholds needs to be developed for Australian conditions which considers insect growth rates.
- Compliance thresholds can significantly increase detection rates when of target densities.

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4.7. *Abbreviations/glossary*

ABBREVIATION	FULL TITLE
CRCNPB	Cooperative Research Centre for National Plant Biosecurity
NBM	Negative Binomial Model
PM	Poisson Model
DLM	Double Log Model
CM	Compound Model
IPM	Integrated pest management
EPP	Emergency plant pest

5. Plain English website summary

Please complete table using plain English. This information will be published on CRCNPB's website for a public audience.

CRC project no:	CRC30086
Project title:	Better sampling strategies for stored grain
Project leader:	Dr. Grant Hamilton
Project team:	Dr. Grant Hamilton (QUT), Dr. David Elmouttie (QUT), Dr. Helen Thompson (QUT), Mr. Phillip Burrill (DEEDI), Dr. Andreas Kiermeier (SARDI)
Research outcomes:	This project has delivered the first review of bulk grain sampling methodologies and statistical techniques since the late 1970's. The review illustrated that a need existed to develop a new sampling methodology that considered how insect species behaved in grain bulks. A new statistical approach was then developed and was shown to outperform

	existing approaches (detect insects) by up to 400 percent. The new approach performed well in all conditions however its benefits were most evident where insects where highly restricted to certain portion of the grain mass. This is an important finding since these types of infestation are common in storages, particularly where infestations are a result of localised factors within storages. Our research has illustrated that, unlike current sampling methodologies based on grain bulk size, sampling programmes are more efficient if based on a fixed numbers of samples. Furthermore, we illustrated that increasing sample number was more important than increasing sample size, particularly where infestation contained in small areas of the grain bulk. This project has developed a statistical methodology, which for the first time allows grain producers and bulk grain handlers to determine at some level certainty how effective their sampling programmes are. Grain producers can use this approach to determine the optimal sample number to maximise detection of pests. Extensions to the approach also allow sampling programmes to be developed for Integrated pest management programmes. This technique, when utilised, will minimise bulk rejections ensuring grain going to storage/port meets the desired level of pest freedom.
Research implications:	Sampling methods in Australia typically are not based on a sound statistical or biological basis. Intake and outturn from bulk handling facilities are the elements of the supply chain most ‘at risk’. Sampling methodologies currently vary significantly among regions and may not provide the level of detection that is required. The new sampling approach as tested against existing statistical detection approaches was shown to provide the highest detection rate of all models examined. This method was also shown to outperform current statistical methods used in Australia. The new sampling method provides a simple method to determine the number of samples required to maximise detection in grain bulks. The model was designed so that it can be adapted to account for varying conditions due to seasonal and geographical variation given appropriate data. The model has been extended such that it can be used for

	IPM where detection at a zero tolerance threshold is not required. Insect detectability has also been incorporated into the model to improve detection estimates.
Research publications:	Elmouttie, D., Kiermeier, A. and Hamilton, G. (2010). Improving detection probabilities in stored grains. Pest Management Science. **66:** 1280-1286. Hamilton, G. and Elmouttie, D. (2011) Insect distributions and sampling protocols for stored commodities. Stewart Postharvest Review. **7**:1-5 Elmouttie, D., Kiermeier, A., Flinn, P., Subramanyam, B., Hagstrum, D. and Hamilton, G. (2012). Sampling stored product insect pests: a comparison of statistical sampling models to maximise pest detection. Pest Management Science (Submitted) Elmouttie, D., Kiermeier, A. and Hamilton, G. (2012). Sampling grain to a compliance threshold: implications for Integrated Pest Management. Pest management Science. (Submitted) Elmouttie, D. and Hamilton, G. (2012). Maximising species detection probabilities in single visit ecological surveys. Acta Oecologia. (Submitted) Elmouttie, D., Hammond, N. and Hamilton, G. (2012). A review of current methodologies for In storage sampling and surveillance in the grains industry. Bulletin of Entomological Research (Submitted)
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