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A review of current statistical methodologies for in-storage sampling and surveillance in the grains industry

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Abstract

Effective, statistically robust sampling and surveillance strategies form an integral component of large agricultural industries such as the grains industry. Intensive in-storage sampling is essential for pest detection, integrated pest management (IPM), to determine grain quality and to satisfy importing nation's biosecurity concerns, while surveillance over broad geographic regions ensures that biosecurity risks can be excluded, monitored, eradicated or contained within an area. In the grains industry, a number of qualitative and quantitative methodologies for surveillance and in-storage sampling have been considered. Primarily, research has focussed on developing statistical methodologies for in-storage sampling strategies concentrating on detection of pest insects within a grain bulk; however, the need for effective and statistically defensible surveillance strategies has also been recognised. Interestingly, although surveillance and in-storage sampling have typically been considered independently, many techniques and concepts are common between the two fields of research. This review aims to consider the development of statistically based in-storage sampling and surveillance strategies and to identify methods that may be useful for both surveillance and in-storage sampling. We discuss the utility of new quantitative and qualitative approaches, such as Bayesian statistics, fault trees and more traditional probabilistic methods and show how these methods may be used in both surveillance and in-storage sampling systems.

Keywords: grains, sampling, surveillance, detection, pests, IPM, surveys

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Introduction

Sampling programmes form an integral component of the grains production and supply industry (Subramanyam & Hagstrum, 1996; Subramanyam *et al.*, 1997; Elmouttie *et al.*, 2010). Sampling occurs throughout the grain production and supply chain and is designed to measure parameters such as grain quality and the presence and abundance of pests (Subramanyam & Hagstrum, 1996). Most modern sampling programmes are based on robust statistical frameworks. From a pest management perspective, statistical sampling methodologies primarily focus on pest detection or pest abundance estimation.

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Grain cultivation and storage occur over vast geographic regions globally, in North and South America, Asia, Europe, Africa and Oceania. Climatic conditions vary substantially throughout these regions, influencing the presence, abundance and persistence of pests both within storages and throughout the broader environment. Because of this, sampling programmes differ significantly depending upon the objective of the programme and the specific characteristics of the geographic region where grain is being produced and stored (Hagstrum & Subramanyam, 2006). For example, sampling strategies to maximise the detection of pests for an individual storage differ from sampling programmes designed to detect pests for a geographic region (Cameron & Baldock, 1998a; Elmouttie *et al*., 2010).

As such, sampling programmes have typically been devised for two distinct scenarios that impact the grains industry. The development of statistical sampling for the detection of pests within storages or shipments (herein defined as in-storage sampling) has historically been a primary focus and received significant attention in the literature (Hunter & Griffiths, 1978; Hagstrum *et al*., 1985; Subramanyam & Harein, 1990; Subramanyam *et al*., 1993; Hagstrum *et al*., 1997; Jian *et al*., 2011). Alternatively and more recently, the need to develop broad scale, statistically robust surveillance methods for pests over larger grain-producing landscapes has been considered (Taylor & Slattery, 2008). Although broad scale surveillance and in-storage sampling pose similar conceptual challenges, in relation to development of statistical methodologies, these issues previously have not been considered together. There are a number of reasons for this. In part, historical development of in-storage statistical sampling strategies has been driven by trade-related objectives rather than science (Jefferies, 2000) and for use in local integrated pest management (IPM) strategies (Hagstrum *et al*., 1985). Many sampling programmes, therefore, have been developed in isolation. Further, although the development of statistically based surveillance methods is not new in disciplines such as epidemiology, the use of these methodologies within the grains industry is relatively novel (Taylor & Slattery, 2008; Hammond, 2010). This review, therefore, aims to outline and compare statistical techniques and methodologies used to develop surveillance and in-storage sampling across the grains industry and other areas to identify techniques that may be used to improve current methodologies.

Sampling within storages – in-storage sampling

Pest detection

Development of statistical sampling methodologies within storages has received significant attention for a number of decades (Hunter & Griffiths, 1978; Hagstrum *et al*., 1985; Lippert & Hagstrum, 1987; Subramanyam *et al*., 1997; Opit *et al*., 2009; Elmouttie *et al*., 2010). Initially, sampling programmes were developed to secure trade routes by ensuring traded grain commodities were pest free (Hunter & Griffiths, 1978; Jefferies, 2000). As a result, sampling strategies were not designed on a robust statistical and biological basis but rather were often based on pragmatic considerations in the grains supply and distribution chain (Jefferies, 2000).

The primary focus of early in-storage sampling systems was the detection of insects at a fixed threshold, e.g. a threshold of zero live insects in grain samples. However, as these early sampling programmes were not based on a solid scientific basis, statistical justification of sampling techniques were often developed after sampling programmes were established (Hunter & Griffiths, 1978; Wilkin, 1991; Jefferies, 2000). As such, statistical sampling methods were often formulated based on assumptions made for convenience rather than being well justified, particularly assumptions relating to pest biology and distribution (Jefferies, 2000).

Sampling for management – IPM

As production and storages developed and management strategies became more sophisticated, the need for more advanced sampling strategies to work in unison with management strategies was recognised (Hagstrum *et al*., 1985; Lippert & Hagstrum, 1987; Subramanyam *et al*., 1993; Athanassiou *et al*., 2011). In contrast to early sampling strategies, newer sampling programmes were recognised as a tool that could be used to improve management of grain storages rather than solely for the detection of pests to ensure commodity pest freedom for trade purposes (Hagstrum *et al*., 1985, 1997; Lippert & Hagstrum, 1987). Fundamental to this change in mindset was the recognition that effective sampling programmes to maximise pest detection and estimate pest abundances needed to be based on an understanding of how pests were spatially distributed within storages (Hagstrum *et al*., 1985). In turn, this led to a consideration of how pest distribution would influence sampling statistics and sampling programmes, and ultimately led to grain specific, statistically based sampling programmes being developed for pests (Hagstrum *et al*., 1985, 1997; Lippert & Hagstrum, 1987; Opit *et al*., 2009; Elmouttie *et al*., 2010).

Unlike sampling programmes developed solely for export or trade that assumed insect distribution to be homogenous for convenience (Hunter & Griffiths, 1978; Wilkin, 1991; Jefferies, 2000; Athanassiou *et al*., 2011), newer sampling programmes attempted to describe spatial partitioning within grain masses and incorporate this into sampling statistics (Hagstrum *et al*., 1985; Lippert & Hagstrum, 1987). Sampling statistics were not based on a single probability distribution, such as a binomial or Poisson, which assumed a uniform spatial distribution, but rather were based on a statistical formulation that described how pests distributed through the grain mass (Hagstrum *et al*., 1985, 1997; Lippert & Hagstrum, 1987). Taylor's power law (Taylor, 1961) formed a fundamental basis of many of these sampling programmes and has been used in a number of studies to accurately describe the dispersion pattern of insects within storages (Hagstrum *et al*., 1985, 1997; Lippert & Hagstrum, 1987; Subramanyam *et al*., 1993, 1997). These approaches used Taylor's power law to incorporate sample to sample variation into sampling statistics. This was first considered by Hagstrum *et al*. (1985), who incorporated sample to sample variation into the double logarithmic model which accounts for "the logarithmic increase in sample units occupied by more than one insect with an increase in mean density" and the "logarithmic increase in the number of insects occupying the infested sample units" to maximise sampling efficiency.

More recently, Elmouttie *et al*. (2010) proposed an approach for sampling grain storages which, unlike many previous methods, was not based on Taylor's power law. The approach explicitly considers that grain storages can be separated into two distinct components, infested and uninfested, and that, within the infested portion of the lot, the intensity of pests needs to be considered. The approach, therefore, considers the

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prevalence of pests within storages and the intensity of pests where they are located. A major benefit of this approach is that parameters are easily estimated as they have direct biological relevance. As such, prior information may be able to be incorporated into the approach which would increase its utility.

Surveillance in grain production

Surveillance is more than just sampling to detect pests within confined spaces. By definition, surveillance is the process of collecting and recording data on pest occurrence and absence (FAO, 2009). As such, surveillance methods vary substantially depending on the system under consideration, and effective surveillance strategies require the backing robust statistics such that data can be interpreted in a meaningful manner. Broadly, surveillance can be separated into two distinct categories, general surveillance, which utilises information gathered from range of sources or specific surveillance, which utilises specific survey techniques to actively target a particular pest species (FAO, 2009). Further and similarly to in-storage sampling, surveillance techniques can be separated into active and passive surveillance, depending on whether the data is actively collected (e.g. field surveys, sampling, trapping) or passively obtained through indirect activities (e.g. questionnaires, prior studies, government data bases) (Hellström, 2008; Kean *et al.*, 2008).

Detection surveys

Detection pest or commodity surveys are used to collect data on the presence or absence of a pest or pests within a defined area. Typically, these survey methods are designed to support claims of pest freedom (McMaugh, 2005). In essence, these types of survey techniques utilise similar sampling statistics as used in in-storage sampling when sampling grain bulks, i.e. sampling to detect pests at a threshold. However, in surveillance, these techniques and statistical methodologies have broader application. For example, such techniques may also be utilised after an incursion of a known pest to demonstrate the success of an eradication programme, that is, verifying area freedom from a pest. In Western Australia for example, the four years of surveillance that was conducted for apple scab post eradication illustrates the use of a detection survey for a verification program (McKirdy *et al.*, 2001).

Delimiting or monitoring surveys

Statistical methods for delimiting survey are designed to demonstrate the distribution of a pest within an area, while monitoring surveys are designed to detect changes of pest intensity in a population (McMaugh, 2005). Delimiting surveys are most commonly utilised in the event of an incursion to determine where pests may be present across a landscape. In contrast, long-term monitoring programmes are more commonly utilised to gather information on established pests and diseases, and statistics are designed to identify temporal change. Although utilised at different stages of the pest incursion and establishment cycle, both surveillance methods have particular relevance to biosecurity, as they provide a means to either establish the area of interest or concern, or to determine the intensity of pests within areas of interest (McMaugh, 2005).

In-storage sampling and surveillance to demonstrate pest freedom

Statistically based surveys to demonstrate pest freedom are becoming increasingly important over a number of industries (Cameron & Baldock, 1998a; Jefferies, 2000; Hammond, 2010). Changes in government regulation, a growing awareness of biosecurity, production of commodities and securing of agricultural trade links have all influenced pursuit of methodologies to ensure and defensibly determine pest freedom (Cameron & Baldock, 1998b; Jefferies, 2000). However, demonstrating that an area or consignment is unambiguously pest free is impossible unless 100% of the area or consignment is inspected. Over small areas, this may be possible; however, within large commodities or over large geographic areas, a total census is not possible due to cost associated with sampling or surveying, the availability of man power and time limitations (Stephens, 2001). Thus, demonstration of pest freedom is reliant on robust statistics and scientific survey methods based on an acceptable level of confidence of detecting a pest if it were present (FAO, 2009).

Historically, pest freedom has been based on an absence of pest detections, with the evidence required to demonstrate freedom dependent on agreements between agencies or trading partners (Jorgensen *et al.*, 2003). This 'lack of evidence approach' used in surveillance is similar to early sampling protocols for grain storages, where pest freedom was demonstrated by sampling at pre-determined rate; and, if pests were not detected, the commodity was deemed pest free (Hunter & Griffiths, 1978). In the International Standards for Phytosanitary Measures (ISPM 4), the need for surveillance is discussed for the establishment, maintenance and verification of pest free areas; however, no guidelines are provided on how surveillance should be conducted (FAO, 2009). A lack of guidelines for sampling storages to display pest freedom is also evident, as, although statistics for many early sampling strategies have been developed to justify entrenched sampling rates, these have typically been developed after sampling strategies have been established and based on assumptions for convenience (Jefferies, 2000).

Evaluating surveillance and in-storage sampling systems

There are a number of qualitative and quantitative methodologies used to evaluate surveillance and sampling systems. The method chosen will vary for a number of reasons. In part, the methodology selected will depend on the type of data that can be accessed, the areas or commodities being sampled, the availability of historical data, and the type of surveillance and sampling that can be conducted. The reason for the surveillance or sampling activity will also have a significant influence on which evaluation process is selected. In general, more robust quantitative methods are required when attempting to prove the presence or absence of a pest, e.g. when establishing pest freedom or when evaluating a pest eradication programme.

Qualitative methodologies

Qualitative methodologies, such as stakeholder questionnaires, expert opinion, fault trees and critical examination, can be used in surveillance and in-storage sampling strategies (Jefferies, 2000; Salman *et al.*, 2003a; Weinburg, 2005). In many countries, such techniques have not been widely adopted; however, stakeholder questionnaires may provide a useful

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tool to monitor pest incursions and for early detection or demonstration of pest freedom within grain producing and storage regions at relatively low cost (Czaja & Blair, 2005; Taylor & Slattery, 2008). For example, surveillance for Khapra beetle (*Trogoderma granarium*), a species not present in Australia, could be strengthened by using stakeholder knowledge to monitor and demonstrate pest freedom over a broad area (Taylor & Slattery, 2008). Furthermore, although questionnaires are a qualitative approach, newer quantitative statistical methods have been developed that can incorporate such data (Martin *et al*., 2005). Bayesian methods, for example, can be adapted to incorporate qualitative data into a quantitative framework (Gelman *et al*., 2004).

Fault tree analysis could also provide a useful methodology for risk analysis of biosecurity threats within the grains industry. The technique has been used to assess the threat of introducing marine species in ballast waters (Hayes, 2002) and for animal health surveillance (Salman *et al*., 2003b). Fault tree analyses have received criticism for their focus on negative events, however, and, as such, surveillance systems based on these methodologies are often criticised (Salman *et al*., 2003b). Moreover, fault tree analyses do not provide quantifiable estimates of the probability that the target pest is absent or present but below a specified prevalence.

Quantitative methodologies

For broad scale surveillance and in-storage sampling programmes, quantitative analyses are becoming increasingly important. The need for robust quantitative analysis in part is to provide a method to compare surveillance and sampling programmes and to determine whether the particular measures undertaken meet the stated objective of the programme (Stephens, 2001; Hammond, 2010). For example, statistical methods developed for sampling grain commodities are used to justify that a particular exporting country's commodities meet the standards prescribed at the time of sale (Jefferies, 2000; Elmouttie *et al*., 2010). Unlike qualitative methods, quantitative methods are repeatable and more transparent. Quantitative methods also provide a robust defendable method to demonstrate issues such as pest freedom or eradication success.

Structured surveys have been the fundamental method for demonstrating pest freedom in broad-scale surveillance and in-storage sampling systems. Structured surveys are commonly used in epidemiology to detect diseases within populations. Using a structured survey, the sensitivity of the survey or confidence level (e.g. detection of a disease), given that the disease is present in the surveyed population, can be calculated at a particular design prevalence (i.e. proportion of the population with the disease: Cannon & Roe, 1982).

A further benefit is that there is a range of methods for calculating sampling intensity and confidence levels for structured surveys in many fields, including epidemiology (Cannon & Roe, 1982; Cameron & Baldock, 1998b), acceptance sampling (Stephens, 2001), ecology (Green & Young, 1993) and pest management (Hunter & Griffiths, 1978; Love *et al*., 1983). Common across all disciplines is that statistical methodologies are based on probability functions, typically the Poisson, binomial or hyper geometric functions. The probability function selected is chosen on the basis of how well it can describe the system being sampled. However, as no statistical function perfectly describes a biological system, approximations are made or inferred (Stephens, 2001).

Although structured surveys can be statistically evaluated when designed correctly, they are typically labour intensive and expensive, particularly when demonstrating pest freedom for pests at low intensity. Further, statistical models that form the justification of structured surveys are often based on assumptions more for convenience rather than a sound biological basis (Jefferies, 2000; Elmouttie *et al*., 2010). In addition, data collected from non-structured surveys and general surveillance are not easily included into analysis, and thus pest freedom must be based solely on the structured survey methods.

Stochastic modelling and scenario trees

Unlike many statistical approaches developed for structured surveys (Love *et al*., 1983; Green & Young, 1993; Stephens, 2001), approaches based on stochastic modelling incorporate variability and uncertainty in model parameters using a probability distribution in place of fixed values (Audigé *et al*., 2003). As such, outputs are described by a range of possible values rather than a fixed value (Vose, 2008). This ability to incorporate variation and uncertainty has seen a number of stochastic modelling approaches being developed for surveillance systems in animal and plant health (Scott & Zummo, 1995; Audigé *et al*., 2001; Fischer *et al*., 2005; Hammond, 2010; Dominiak *et al*., 2011) as biological variation in the form of uncertainty can be incorporated into models. Stochastic simulation models may also be used to evaluate surveillance systems for the demonstration of pest freedom and to compare the sensitivity of surveillance strategies.

Scenario trees are constructed to display all the possible scenarios that could occur in the system being analysed (Hoyland & Wallace, 2001; Martin *et al*., 2007a; Hadorn *et al*., 2009). In this respect, they are similar to fault trees, as they map out the system; however, they differ by displaying all possible scenarios not just potential faults (Salman *et al*., 2003b). Further, scenarios trees have probabilities assigned at each node of the tree, allowing quantitative analysis of particular pathways to be assessed (Salman *et al*., 2003b; Martin *et al*., 2007a).

Scenario trees have been used to model surveillance systems and to demonstrate freedom in animal health (Hueston & Yoe, 2000; Martin *et al*., 2007a) and for fungal pathogens in wheat (Hammond, 2010). A major advantage of scenario trees is that they are transparent, providing a clear description of the surveillance system and methods used (Stärk, 2003; Martin *et al*., 2007a). In addition, scenario trees may be combined with alternative methods such as stochastic modelling techniques to provide robust quantitative analysis of surveillance sensitivity (Stärk, 2003). Although used in broader surveillance systems, stochastic modelling and scenario trees have not been used to demonstrate pest freedom in in-storage sampling programmes for detection, such as those used in grain storages. In part, this relates to data outputs not being favoured by end users, as these methods do not provide a definitive answer, rather a range of potential scenarios and probabilities associated with each outcome. Additionally, scenario trees can be time consuming to construct and data to estimate parameters may be limited.

Bayesian modelling

Bayesian approaches are growing in popularity in both surveillance and sampling systems due primarily to their ability to incorporate a range of data types. Expert opinion, qualitative data, prior knowledge, alternative data types, as well as uncertainty, can be incorporated into Bayesian analysis, making them extremely powerful (Gardner, 2002; Wagner *et al.*, 2003; McCarthy, 2007). Bayesian methods have been used to incorporate information on disease status to demonstrate disease freedom in cattle (Audigé *et al.*, 2001), as well as in conjunction with scenario trees incorporating historical surveillance evidence (Martin *et al.*, 2007a,b). Methods have also been adapted for use in epidemiology to calculate disease prevalence, sample sizes, and estimate test sensitivity and specificity (Gardner, 2002; Branscum *et al.*, 2004, 2005; Johnson *et al.*, 2004). As such, Bayesian methods are applicable over a broad range of surveillance and sampling systems due to their flexibility, and may provide significant advances to surveillance and sampling systems within the grain production and storage systems due to the type of data that can be incorporated.

Combining broad scale surveillance and in-storage sampling systems in grains

Throughout this review, a range of methodologies have been discussed, some designed specifically for surveillance, some designed for in-storage sampling and others designed for alternative uses that may be applicable to both surveillance and in-storage sampling. Of interest is that many of the 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 where production, storage and export of grain occurs over large geographic regions, it would make sense if broad-scale surveillance and in-storage sampling systems were streamlined, such that methodologies, data collection and data analysis are conducted uniformly across industry.

In part, the separation between broad-scale surveillance and in-storage sampling has been historical. In-storage sampling techniques primarily arose as a response to poor hygiene in storages limiting market access (Jefferies, 2000). As such, although structured surveys (sampling) have formed the basis to many sampling strategies, methodological development was *ad hoc* and based purely on practical restrictions rather than science (Jefferies, 2000). Further, many of the statistical methodologies, although fundamentally similar to those used in surveillance today, were based on assumptions of a homogenous distribution of pests throughout the grain mass (Wilkin, 1991; Jefferies, 2000; Athanassiou *et al.*, 2011) although insects have been shown to be heterogeneously distributed (Hagstrum *et al.*, 1985). In contrast, sampling methodologies developed throughout the 1980s and 1990s for use in grain storages were developed primarily for IPM purposes (Hagstrum *et al.*, 1985; Lippert & Hagstrum, 1987; Subramanyam *et al.*, 1997). Although statistically robust, these methods are not focused on detection but rather on mean abundance estimation and, as such, have limited suitability for the demonstration of area freedom that is required in surveillance. Furthermore, parameter estimation of the methodologies is typically data intensive, requiring extensive data to calibrate models and making them unsuitable for surveillance activities where data can be limited.

Statistically based surveillance methods for biosecurity, in contrast, are a relatively new concept for the grains industry (Taylor & Slattery, 2008). Methods to maximise surveillance successes and quantify surveillance strategies have been considered from a number of fields, including epidemiology, ecology and plant pathology. A number of methodologies developed for surveillance, which could be used for surveillance systems in grains, 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. Although structured sampling is undertaken in grain storage to detect pests, such methods do not incorporate varied risk throughout the production and storage network. Pest intensity in storage is known to fluctuate in relation to a number of factors, including hygiene, storage type and climatic conditions (e.g. temperature and humidity: Hagstrum, 1996; Rees, 2004). It would be of great benefit to producers and storage managers if in-storage sampling programmes could account for the variation in pest intensity (risk) associated with such factors. Stochastic scenario trees could provide a mechanism to incorporate risk relating to different regions, farms or even geographic areas to better inform and parameterise sampling models. Hadorn *et al.* (2009) demonstrated that stochastic scenario trees could be used to develop a cost effective surveillance system for Bluetongue virus, BTV (an insect borne viral disease of ruminants) in central Europe. Similar to insect pests within storage, which vary in intensity and distribution (Hagstrum *et al.*, 1985), BTV is a vector-borne viral disease that is present at different prevalences and intensities within a population over a geographic area. Hadorn *et al.* (2009) demonstrated that stochastic scenario trees could be used to better allocate surveillance resources where disease or pest prevalence varied and, therefore, improve the cost effectiveness of surveillance and sampling systems.

Methodologies and current data collection practices from in-storage sampling may also be of benefit to surveillance strategies. Structured surveys that are currently standard practice in the grains storage network, both on farm and in bulk storage, would provide significant benefits in the development of state or nationwide surveillance systems. From a broad-scale surveillance perspective, although structured surveys provide a robust quantifiable method for determining pest freedom and eradication success, they are usually cost prohibitive due to the areas that need to be sampled or surveyed. The data collected from individual storage and bulk handling facilities, however, would be invaluable for surveillance. Furthermore, if industry could modify sampling systems into a uniform regional or nationwide system, broad-scale surveillance could be improved substantially and for relatively little cost, as sampling activities are already undertaken for pest management purposes. Using such data from existing storage, would also aid in demonstrating freedom of pests, such as Khapra beetle, from countries were it remains absent, such as Australia.

Bayesian methods may provide the greatest gains to grains surveillance and in-storage sampling systems. 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 are of value, the information 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. Bayesian techniques can allow for a range of data types to be incorporated into a single analysis (Marcot *et al.*, 2001). Furthermore, Bayesian analysis can be used to incorporate expert opinion as prior information. 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. 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.

There are existing methodologies that could benefit from the incorporation of alternative data sources. Elmouttie *et al.* (2010) proposed a methodology for sampling grain storages that overcomes the shortfalls of traditional techniques and, in many respects, is similar to techniques to demonstrate freedom in targeted surveys in epidemiology. The technique considers that both the prevalence and intensity of individuals within an area has an influence on the probability of detection. However, unlike techniques based on the hypergeometric or binomial functions (Cannon & Roe, 1982; Cameron & Baldock, 1998a), the method proposed by Elmouttie *et al.* (2010) explicitly considers that pests may be heterogeneously distributed. The methodology proposed contains two parameters that need direct estimation, the prevalence of pests and their intensity. As these parameters are a direct translation of a biological occurrence, the authors suggested that they may be estimated from a number of data sources. As such, Bayesian methodology to incorporate multiple data forms with uncertainty may provide a valuable tool for sampling models for in-storage sampling and surveillance systems.

Conclusion

Sampling and surveillance systems form a major component of the grain supply, production and biosecurity system and their importance will continue to grow into the future. A number of statistical techniques designed to justify pest freedom in grain sampling and in surveillance are conceptually similar, and, hence, coordination of sampling strategies would benefit the grains industry. The development of techniques based on stochastic scenario trees and Bayesian analysis may provide a means to (i) make sampling more cost effective by targeting sampling where most required and (ii) allow for alternative data sources to be incorporated into existing sampling plans and methodologies. An area where significant improvements to both surveillance and in-storage sampling can be made is the use of all available data. Systems need to be developed such that sampling and surveillance strategies become intertwined and data is shared to maximise biosecurity and pest management outcomes.

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