Comprehensive REVIEWS in Food Science and Food Safety

Systematic Review of Methods to Determine the Cost-Effectiveness of Monitoring Plans for Chemical and Biological Hazards in the Life Sciences

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Abstract: This study reviews the methods used to determine the cost-effectiveness of monitoring plans for hazards in animals (diseases), plants (pests), soil, water, food, and animal feed, and assesses their applicability to food safety hazards. The review describes the strengths and weaknesses of each method, provides examples of different applications, and concludes with comments about their applicability to food safety. A systematic literature search identified publications assessing the cost-effectiveness of monitoring plans in the life sciences. Publications were classified into 4 groups depending on their subject: food safety, environmental hazards, animal diseases, or pests. Publications were reviewed according to the type of model and input data used, and the types of costs included. Three types of models were used: statistical models, simulation models, and optimization models. Input data were either experimental, historical, or simulated data. Publications differed according to the costs included. More than half the publications only included monitoring costs, whereas other publications included monitoring and management costs, or all costs and benefits. Only a few publications were found in the food safety category and all were relatively recent studies. This suggests that cost-effectiveness analysis of monitoring strategies in food safety is just starting and more research is needed to improve the cost-effectiveness of monitoring hazards in foods.

Keywords: cost-effectiveness, food safety, hazards, models, monitoring

Introduction

Contaminated food sold on the market has the potential to cause serious health damage to humans upon consumption. In addition, companies supplying contaminated food to the market run the risk of high recall and disposal costs, reputational damage, and loss of consumers' confidence in the company, potentially resulting in temporary or even structurally, lower sales (Hussain & Dawson, 2013; Thomas et al., 2015). Furthermore, the General Food Law in Europe stipulates that "Food shall not be placed on the market if it is unsafe" (Regulation 178/2002/EC). It is therefore in the interest of consumers, food companies, and the government to strictly monitor food hazards, to ensure that these hazards do not become a risk for public health. A monitoring plan should consider not only accuracy, but also the budget available for monitoring, which is generally limited. Given limited resources, a batch of food or a daily production cannot be tested endlessly. This highlights the importance of monitoring in a cost-effective way to achieve the highest accuracy for a given budget.

Prior to undertaking this research, we observed that only very few studies had addressed the cost-effective monitoring of hazards in food. Monitoring schemes in the field of food safety tend to focus only on accuracy and not on costs. Including the costs in the design of the monitoring plan may improve accuracy at the same cost, or it may lead to cost savings while achieving the same accuracy (Lascano-Alcoser et al., 2013). To assess the cost-effectiveness of monitoring hazards in food, adequate methods to determine cost-effectiveness are needed. A large body of research addresses the cost-effective monitoring of hazards in other fields, such as animal and plant diseases and soil and water contaminants. Methods used in these fields might also be applicable to food safety issues, where many hazards are monitored but cost-effective monitoring schemes are frequently lacking. A review of the methods used to determine the cost-effectiveness of monitoring in different fields can provide insight into the applicability of methods for the field of food safety. Including different fields is particularly relevant because researchers tend to focus on publications from their own discipline and different disciplines develop their own methodological procedures.

The objective of this study was to identify and review methods for evaluating the cost-effectiveness of monitoring hazards in

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Table 1–Search strings used in the different databases utilized for this study.

Database	Search string
Scopus	(TITLE(monitoring OR sampling OR testing OR surveillance OR screening) AND TITLE-ABS-KEY ((cost* OR economic* OR resource*) AND (effective* OR efficien* OR optim* OR allocation))) AND PUBYEAR > 1999 AND PUBYEAR < 2017 AND (LIMIT-TO(DOCTYPE,"ar") OR LIMIT-TO(DOCTYPE,"ch")) AND (LIMIT-TO (LANGUAGE,"English")) AND (LIMIT-TO(SUBJAREA,"ENVI") OR LIMIT-TO (SUBJAREA,"AGRI") OR LIMIT-TO (SUBJAREA,"SOCI"))
PubMed	(((monitoring [Title] OR sampling [Title] OR testing [Title] OR surveillance [Title] OR screening[Title])) AND ((cost? OR economic* OR resource*) AND (effective* OR efficien* OR optimiz* OR allocation))) AND ("2000/01/01"[PDat]: "2016/12/31"[PDat]) AND Animals[Mesh:noexp]
CAB Abstracts	TI (monitoring OR sampling OR testing OR surveillance OR screening) AND (cost? OR economic* OR resource*) AND (effective* OR efficien* OR optim* OR allocation) NOT SU (man OR human) NOT SU (gene* OR DNA OR RNA). Limiters: Publication year: 2000 to 2016, Publication type: journal article, book, Broad category: Animal Sciences, Plant Sciences, Ecology & Environmental Sciences, Agricultural Economics & Rural studies Language: English.

As the databases covered a broad area of subjects, and as the keywords did not specify the field, extra limiters were added. In PubMed, one can choose between "human" or "other animals." The limiter "other animals" was chosen to eliminate the large amount of human health studies. In Scopus, the subject was limited by choosing the topics "agricultural and biological sciences," "social sciences," and "environmental science" and the document type was set to articles or book chapters. In CAB Abstracts, the broad category was set to animal sciences, plant sciences, ecology and environmental sciences, agricultural economics and rural studies, the publication type to journal article and books, and the language to English. As CAB Abstracts included a detailed list of subjects for each article, it was used to remove a large amount of articles about human diseases by adding the string "NOT SU (man or human)" and to remove many articles about DNA testing or resistance screening by adding the string: "NOT SU (gene* or DNA or RNA)".

the life sciences by performing a systematic literature search and review. The review aimed to assess the strengths and weaknesses of all available methods, to provide examples, and to discuss the methods in the context of food safety.

Materials and Methods

Literature search

This review focused on studies assessing the cost-effectiveness of monitoring biological and chemical hazards in the life sciences, excluding human diseases. The review was therefore restricted to studies related to plant and animal pests and diseases, food and feed safety, and soil and water contaminants. A hazard was defined in this study as: a chemical, biological, or physical component or species that has the potential to cause damage to human, plant, or animal health.

A systematic literature search was conducted to identify methods currently used to assess the cost-effectiveness of a monitoring plan. The search method was developed beforehand. Electronic databases were used to gather sources from the scientific literature. The selected databases were Scopus, PubMed, and CAB Abstracts. These three databases were expected to provide a sufficiently large initial sample of peer-reviewed publications. Scopus is a very large database that includes peer-reviewed publications on a variety of topics: science, including medicine, technology, social sciences, arts, and the humanities (Elsevier, 2017). CAB Abstracts focuses on the life sciences and includes topics such as agriculture, applied economics and sociology, animal sciences, plant sciences, environmental sciences, biotechnology, chemistry, climate change, food sciences, human nutrition, leisure and tourism, pharmacology, microbiology, natural resources management, and veterinary medicine (CAB Abstracts, 2017). PubMed also focuses on the life sciences.

The research question was formulated prior to the literature search as: What methods are used to determine the cost-effectiveness of monitoring plans for hazardous components in the life sciences? Relevant keywords were also identified prior to the search: "monitoring," "hazardous components," and "cost-effectiveness." The keyword "hazardous components" was not included in the search string because it had too many synonyms and the search would miss important information if some synonyms were omitted from the search string. To find the best search strings, several publications from different fields were 1st read to identify different terms used for a specific subject. For example, synonyms frequently used for monitoring were "surveillance," "sampling," "testing," and "screening." Synonyms used for the concept of costs were "cost,“ "economic,“ and "resources.“ Finally, synonyms used for the concept of effectiveness were "effective,“ "efficiency,“ "efficient,“ "optimal,“ "optimization,“ and "allocation.“ The initial search string used to search the three databases was: "(monitoring or sampling or testing or surveillance or screening) and [(cost? or economic* or resource*) and (effective* or efficien* or optim* or allocation)]," using the wildcards "*" for 0 to n characters, and "?" for 0 or 1 character. Table 1 shows the exact search terms used and provides an explanation of the terms added to the initial search string in the different databases.

The records obtained from the initial database searches were then included or excluded according to the following 6 criteria.

(1) Type of publication: Published peer-reviewed primary research papers and book chapters.
(2) Language: Studies written in English.
(3) Date: Studies published between January 2000 and December 2016.
(4) Subject: The studies were about monitoring hazards, where hazards followed the definition used in this research. Studies that were not about monitoring hazards, such as resistance screening and biodiversity monitoring, were excluded. Validation studies of a particular analytical method were excluded, as these do not include cost calculations. Natural disasters (floods, fires, or rain) were also excluded, as these hazards were not considered to have the same direct impact on plant, animal, or human health as a disease would. Studies assessing the number of wildlife were also excluded, as this was considered biodiversity monitoring. However, the review included studies on monitoring pests with the potential of harming plants (forest pests) or humans (mosquitoes) directly, or indirectly as a vector of a disease (mosquitoes). Finally, studies on human diseases were excluded. Although much research is available on the cost-effective monitoring of diseases in human populations, this field has different ethical considerations.
(5) Assessment of costs and effectiveness: Both the costs and the effectiveness of monitoring plans were quantitatively assessed, or assessed with at least a few qualitative classes. Only stating that the method was cost-effective in the introduction or conclusion was not considered sufficient to include the publication. Effectiveness was defined as the extent to which a target was achieved. Costs could be expressed in monetary terms, in time, or in other resources.
(6) Key words: The search was restricted to references with the key word "monitoring" in the title, or the synonyms "surveillance," "sampling," "testing," and "screening." The words "cost" and "effectiveness" were also required, but

these terms could be present in the title, abstract, or the keywords. The following synonyms were included: "cost," "economic," "resources," "effective," "efficiency," "optimal," "optimization," and "allocation."

The search of the three databases using these search strings was expected to provide a set of relevant publications covering a large fraction of all available publications. This set became a starting point to find additional relevant publications, by using the snowballing technique to find publications in the reference lists of the selected publications.

The citation manager Endnote was used to combine the references found in the search and to remove the duplicates. The remaining references were then sorted into two groups based on the title: a group containing references with relevant titles and references for which the relevance was unclear after reading the title, and a group containing irrelevant titles for this study. Irrelevant titles were titles that did not meet the following inclusion criteria: English title, addressing monitoring hazards except human diseases. After discarding the references with irrelevant titles, the remaining references were filtered based on their abstracts. Again, 2 groups of references were made: a group of studies with a relevant abstract and another group of studies with irrelevant abstracts that did not meet the following inclusion criteria: addressing monitoring hazards expect for human diseases, the idea of effectiveness and costs were mentioned. Finally, the full text of the remaining relevant publications was read, focusing on the methods section. References were excluded at this stage if the full text could not be accessed, if the text was not in English, or if there were no quantitative calculations or qualitative assessments with classes of the effectiveness or costs of a monitoring plan (criterion 5).

After gathering the list of relevant references using the systematic database search, the snowballing technique was applied. The reference lists in the selected publications were screened to find additional relevant publications. The procedure to determine relevance was identical to the procedure followed for the database search. The relevant publications were then added to the set obtained from the database search.

Classification of the relevant publications

The final set of selected studies was inserted in an Excel file. The publications were divided into 4 categories according to subject: animal diseases, food and feed safety (hereafter termed food safety), environmental hazards (soil and water), or plant diseases/pests/invasive species (hereafter termed pests). The hazard studied and the methods used were recorded in the Excel file for each publication. The methods used in the studies were classified according to 4 criteria:

(1) Input data: experimental/historical or simulated.
(2) Type of model: simulation model, optimization model, or statistical model.
(3) Treatment of uncertainty: deterministic or stochastic model.
(4) Cost items taken into account: only monitoring costs, monitoring, and management costs, all direct costs and benefits, or all costs and benefits including indirect effects (for example, market effects).

(1) Input data: Input data can be experimental, historical, or simulated. Experimental and historical data differ according to how they are generated: experimental data are generated from an experiment that controls for the influence of external factors, whereas historical data are collected from real life situations where these influences are not controlled. We were only interested in whether the results were based on actual or simulated data, and therefore experimental and historical data were considered as a single category. Advantages of using historical and experimental data are that the results are based on real-life data and no assumptions are made. However, a large-scale experiment or a large dataset with historical data is needed to obtain statistically significant results. Alternatively, input data can be simulated or calculated. For example, the sensitivity of a surveillance program can be assessed with a model. Although the parameters are usually based on historical data, the data used to draw conclusions are calculated or simulated. Advantages are the potential to incorporate uncertainty, for example by using a distribution to represent a parameter, and the ability to model situations where no data are available. The main disadvantage is that results are based on an assumption, an approximation, or a calculation with a formula or model, which might not reflect reality.

(2) Type of model: Studies can use a statistical model, a simulation model, or an optimization model. A statistical model is defined as an empirical model based on data (observations). A statistical model describes and summarizes data, and it uses the data to approximate reality and draw conclusions and to explore the relationships between variables (Ott & Longnecker, 2010). A simulation model is a mathematical model that predicts the impact of some inputs and decisions on an output parameter (Winsberg, 2003). Performance of different monitoring programs can be compared by changing input parameters. In contrast, an optimization model aims to find optimal levels for some (decision) variables. For example, an optimization model can be used to minimize the total costs of a surveillance program by choosing the optimal set of monitoring activity levels. No advantages and disadvantages of the three model types can be summarized, because the methods have different aims.

(3) Treatment of uncertainty: The models were classified as either deterministic or stochastic models according to how they treated uncertainty. Models with both deterministic and stochastic parts were considered as stochastic models in this research. A deterministic model has a unique set of outputs, which are determined by the input parameter values and the initial conditions. An average or expected result can be determined (Bolker, 2007). A worst- or best-case scenario can be estimated by considering more extreme values for the input parameters. A deterministic model can provide results and predictions quickly and the results are also easy to interpret. However, these results do not include variability or uncertainty in the model or its inputs, and therefore, the likelihood of each outcome cannot be assessed.

A stochastic model includes random variables with associated probabilities to account for natural variability and uncertainty. A random variable can, for example, be represented by a discrete or continuous probability distribution. An expected value can be found in this way (Dijkhuizen & Morris, 1997). Another option is to use a set of simulated random input variables and to record the output. This procedure is repeated many times with different sets of input variables. The final output is a distribution of outputs from the different simulations, enabling the probability of an outcome to be assessed. A Monte Carlo simulation is frequently used to generate random samples from distributions, and it shows all the possible outcomes and their likelihoods (Fortin & Langevin, 2012; Martins et al., 2017). The advantage of a stochastic model is that it includes model and input variability and uncertainty and generates a distribution of possible outcomes. However, for complicated systems, only a limited number of events can be integrated in the stochastic simulation, making it difficult to draw a clear conclusion.

(4) Cost items taken into account: Finally, the methods were compared according to the cost items that were taken into account: only monitoring costs, monitoring and management costs, all direct costs and benefits or all (direct and indirect) costs and benefits. Monitoring costs can be measured as the time needed to sample and analyze, or as the material and labor costs of the analytical test. Including only monitoring costs is straightforward and requires the least data. However, this approach does not include the consequences of better or worse monitoring, even though these costs can be more important than the monitoring costs alone. Another approach is to consider both monitoring and management costs: management costs are the costs of actions that need to be taken after a contamination has been detected, for example culling, recall, eradication.

A 3rd approach is to consider all the costs and benefits of monitoring by using the partial budgeting method. Partial budgeting can be used to compare the costs and benefits of alternative monitoring plans. It focuses on the added returns, the reduced costs, the added costs, and the reduced returns of each monitoring plan (Dijkhuizen & Morris, 1997). An example of added returns is the improved productivity due to fewer animal diseases (Tambi et al., 2004); an example of reduced costs is the avoided recall cost; an example of added costs is the costs of the monitoring program and the management costs in case a contamination is found; and finally an example of reduced returns might be related to slower production in case of lengthy monitoring plans. The net effect can be summarized as the total benefits minus the total costs. Partial budgeting enables both costs and benefits to be compared. However, the method requires benefits to be expressed in monetary terms, which might not always be easy to obtain.

Finally, the market effects of a contamination can be estimated using a partial equilibrium model, a model of supply and demand in a market. This type of model only considers markets that are directly affected, that is, it excludes interactions between different markets in an economy. A partial equilibrium model accounts for the effects of an outbreak, contamination, or pest invasion on supply and demand (Surkov, Oude Lansink, & van der Werf, 2009). This method is complex and requires a detailed background in economics. Table 2 provides a summary of the advantages and disadvantages of the different approaches.

After classifying the publications according to the type of data and models used and the cost categories included in the analyses, these aspects were compared across the different categories of hazards. The results section presents this comparison and provides examples of the different types of methods from different fields.

Results and Discussion

This chapter starts with presenting the results of the literature search and the results of the classification of the relevant publications. After that, the methods used in the publications harvested are discussed and examples are given for each method. The section on discussing the methods is divided into three parts: (a) input data, (b) model types, and (c) assessment of costs. Then, the 4th section, on food safety, discusses the applicability of the different methods to food safety hazards. The final section of this chapter discusses the limitations of the search method used.

Literature search

The database search was conducted in January 2017. A total of 8,914 publications were found in the three different databases (4,212 in Scopus, 3,747 in CAB Abstracts, and 955 in PubMed). After removing the duplicates, 7,207 results remained. These results were filtered based on their titles, resulting in the exclusion of 6,425 titles. The set of remaining relevant titles was then filtered by reading the abstracts: as a result 606 abstracts were excluded. Finally, the full texts of the remaining 176 publications were read and a final set of 78 publications was selected. The snowballing technique was then applied. After screening the reference lists of the 78 selected publications, 79 additional titles were considered relevant. After reading the abstracts, 28 of these 79 publications remained. Finally, after reading the full texts, 21 additional publications were considered relevant and added to the 78 publications previously found. The analysis in the remainder of the study is based on these 99 references. The selection process and the exclusion criteria are depicted in Figure 1.

Classification of the relevant publications

The different methods used in the different categories are summarized in Table 3. Only nine publications were classified in the category food safety, whereas the categories of animal diseases and pests had 35 publications each. Finally, 17 publications belonged to the category environmental hazards. Three publications did not fit within a category and were therefore placed in a separate group of general publications. The 99 references are listed according to category in the appendix.

The results of the literature search confirmed our initial observation that very little research has been undertaken on cost-effective monitoring of hazards in food safety. The publications on monitoring food safety were from 2007 onwards, and therefore more recent than publications from other fields. This research originated from only three countries: Denmark (four references), the United States (three references), and The Netherlands (two references). These results show that research on cost-effective monitoring in food safety is scarse and relatively recent. The methods used in this category are similar to the methods used in other categories, except that no studies using experimental data with a statistical model were found.

Analysis of the methods used

The pests category differed from the other categories, because studies in this category used more experimental data, deterministic models, and statistical models than studies in the other categories. In the pests category, experiments are relatively easily designed and conducted. Examples of experiments include experiments to test different insect traps, to compare different water sampling methods, or to compare the performance of different sampling techniques for insects. In contrast, setting up an experiment with artificial contamination from a hazard is less feasible in the categories of environmental sciences, animal diseases, and food safety. Stochastic simulation models were the most frequently used models in the category animal diseases, because it is difficult to experiment with diseases. Stochastic variables were frequently used in this category.

Table 2–Summary of the advantages and disadvantages of the different methods discussed in this study.

	Method	Advantages	Disadvantages
Input data	Actual	+ Results are straight-forward + No assumptions	– An experiment has to be set up, or a dataset with historical data is needed. – The results are only based on the results of the experiment or on the historical data.
	Simulated	+ Uncertainty can be incorporated: a parameter can be represented by a distribution for example.	– Based on assumptions, calculations, formulas, approximations: might not be exactly the same as in real life.
Uncertainty	Deterministic	+ Easier to interpret than a stochastic model	– Results are determined, fixed, no uncertainty is incorporated. – The likelihood of each outcome is not assessed.
	Stochastic	+ Uncertainty is included + All the possible outcomes are shown and how likely they are.	– In complicated systems, only a limited amount of events can be integrated in the simulation. – The conclusions are not always straight-forward.
Assessment of costs	Only monitoring costs	+ The easiest way to compare different monitoring strategies. + Not much data is needed.	– Damage costs or benefits are not considered, which might be more important than the sampling costs.
	Monitoring and management costs	+ Management costs are considered as well: might be less with better monitoring.	– Benefits are not considered.
	All direct costs and benefits	+ All different aspects of the costs are considered + Costs and benefits can be easily compared.	– Data is needed on benefits in terms of costs.
	All (direct and indirect) costs and benefits	+ All aspects are taken into account.	– Data needed. – More complex than the other approaches: an economical background is needed.

Table 3–The different methods used to assess the cost-effectiveness of a monitoring plan.

		Animal diseases	Food and feed safety	Environmental hazards (soil and water)	Pests	Total (including general papers)
Number of publications		35	9	17	35	99
Input data	Experimental/historical data	3 (9%)	0 (0%)	2 (12%)	15 (43%)	20 (20%)
	Simulated	32 (91%)	9 (100%)	15 (88%)	20 (57%)	79 (80%)
Uncertainty	Deterministic	7 (20%)	2 (22%)	5 (29%)	22 (63%)	38 (38%)
	Stochastic	28 (80%)	7 (78%)	12 (71%)	13 (37%)	61 (62%)
Model type	Statistical	3 (9%)	0 (0%)	2 (12%)	14 (40%)	19 (19%)
	Simulation	27 (77%)	4 (44%)	7 (41%)	7 (20%)	47 (47%)
	Optimization	5 (14%)	5 (56%)	8 (47%)	14 (40%)	33 (33%)
Assessment of costs	Only monitoring costs	20 (57%)	5 (56%)	11 (65%)	17 (49%)	56 (57%)
	Monitoring and management costs	6 (17%)	1 (11%)	3 (18%)	8 (23%)	18 (18%)
	All direct costs and benefits	9 (26%)	3 (33%)	3 (18%)	9 (26%)	24 (24%)
	All (direct and indirect) costs and benefits	0 (0%)	0 (0%)	0 (0%)	1 (3%)	1 (1%)

The cost items considered had a similar distribution in all categories: approximately half of the references in each category only considered the monitoring costs, a quarter included management costs, and the remaining quarter estimated both the costs and benefits. In the following subsections, the input data, models, and the assessment of costs are discussed in more detail with the use of examples.

The following sections describe the input data used, the model types and the assessment of costs using examples from the publications retrieved by the search. These examples are chosen in order to represent at best all fields and all different methods deemed relevant from the literature study.

Input data

Experimental and historical data were used more often in the pests category than in the other categories. This type of data was used in 15 of the 35 publications. Puckett (2013) designed an experiment to test the effectiveness of 6 different traps for phorid flies. The design was as follows: a grid was set on an aerial map, 20 sampling blocks (replicates) were selected, six sampling points within each block were chosen, and the traps were set. The traps were then brought to the lab for further assessment. Tunks, Parsons, Vazquez, and Vroblesky (2005) designed an experiment to compare diffusion samplers with conventional samplers for groundwater contamination. In the research by Hodgson, Burkness, Hutchison, and Ragsdale (2004), 10 commercial soybean fields were sampled and analyzed for pests for a period of 3 years.

Simulated data were the preferred type of data in all categories. For example, a scenario tree model was frequently used in the category animal diseases to estimate the sensitivity of a monitoring plan. The review shows that very few historical data were available; assumptions and formulas were used to fill the gaps. Future research could be improved if large datasets become available, which can be shared and combined to improve the reliability of the research conducted.

Model types

Three categories of models were differentiated: statistical models, simulation models, and optimization models. Statistical models were used in 14 of the 35 publications in the pests category. Rosado et al., 2014 compared different sampling plans for pest mites on nuts. They analyzed the results of their experiment using different statistical tools and models: T -test, ANOVA, Tukey's test, and linear regression. An example of a statistical model in the category animal diseases is the study of van Schaik, Pradenas, Mella, and Kruze (2007), who compared the

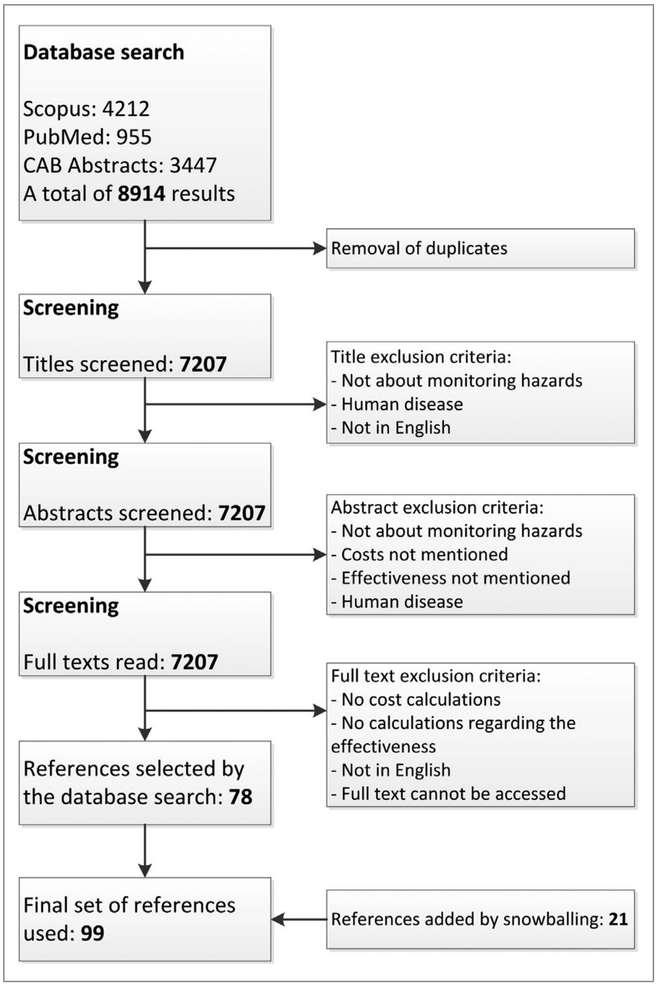

Figure 1–The selection process of the relevant literature harvested for this study (the search was finalized early January 2017).

sensitivity of two paratuberculosis tests: a fecal culture on pooled samples versus a less sensitive ELISA test. Blood and fecal samples were collected from commercial farms in Chile. The study used Fisher's exact test to determine the difference in sensitivities.

In general, simulation models were used most frequently (47%) and statistical models were used least frequently (19%). However, the proportions differed across the categories of hazards. Simulation models were used most frequently in the category animal diseases (77%), a large percentage of these were scenario tree models. Simulation models were used to simulate the transmission of a disease in animals, the spread of a pest population, the spread of a chemical in soil or water, and the probability that a monitoring plan detects a hazard.

Optimization models were used in one third of all publications, and they were used relatively more frequently in the categories food safety (five of the nine publications) and environmental hazards (eight of the 17 publications). Methods used to solve these optimization problems were genetic algorithms, simulated annealing, linear programming, and stochastic dynamic programming (SDP). Simulated annealing was used by Nunes, Cunha, and Ribeiro (2004) to optimize groundwater monitoring. One station at a time was replaced and the result was evaluated with regard to the objective function and whether the Metropolis criterion was fulfilled. A decision was then made to either keep or reject the change. Simulated annealing was, however, only able to find optimal local solutions (Nunes et al., 2004). A genetic algorithm is a method used to solve an optimization problem and is based on the Darwinian principles of natural evolution (McCall, 2005). Genetic algorithms were frequently used in the category environmental hazards, for example by Reed, Minsker, and Valocchi (2000) and Reed, Minsker, and Goldberg (2001), to optimize groundwater monitoring. In these studies, fitness values, which are measures of quality, were assigned to each sampling plan and were used to determine which sampling plans were allowed to reproduce and make a new population. Several iterations were made and a new population was created each time until the genetic algorithm converged (Reed et al., 2000). NGSA-II is a second-generation non-dominated sorting genetic algorithm developed by Deb et al. (2002) to rapidly solve multi-objective optimization problems (Deb, Pratap, Agarwal, & Meyarivan, 2002). This technique was used by Reed and Minsker (2004) to optimize groundwater monitoring. The objectives of this optimization problem were to minimize the sampling costs, maximize the relative accuracy of local concentration estimates, maximize the relative accuracy of global mass estimates, and minimize the estimation uncertainty.

SDP is a method used to optimize an objective function for a fixed period. Moore et al. (2010) used this method to find an optimal budget allocation for surveillance of invasive species on an island. The model calculated the optimal allocation for a fixed time period by applying an iterative backward process. By starting at the final time spot, the process accounted for future expected costs of invasive species. The SDP stepped back to the previous time period and calculated the expected costs for each decision and repeated this for each time period. The optimal decision for each state was then found (Moore et al., 2010).

Linear programming was used, for example, by Lascano-Alcoser, Velthuis, van der Fels-Klerx, Hoogenboom, and Oude Lansink (2013) to determine the optimal level of monitoring activities for dioxins in milk. Linear programming requires the specification of a linear objective function to be minimized or maximized by changing decision variables, given some constraints (for example, limited resources). The feasible region contains the solutions that satisfy all the constraints. Within the feasible region, the optimal solution has the most favorable value for the objective function. The simplex method considers the corner points to find the optimal solution (Dijkhuizen & Morris, 1997). Yemshanov et al. (2015) circumvented the requirement for a linear objective function by using a piecewise approximation of a nonlinear objective function.

Multi-objective optimization models were encountered a few times. Bode, Nowak, and Loschko (2016) estimated Pareto-optimal solutions for their multi-objective optimization model to optimize groundwater monitoring. The 1st objective was to detect with maximum probability all possible future contaminations. The second objective function was a maximum early-warning time for installing counteractions. The third objective function was to minimize costs. The first two objective functions relied on model-based predictions and Monte Carlo simulations were used to include uncertainty.

Vos, van der Goot, van Zijderveld, Swanenburg, and Elbers (2015) combined a stochastic simulation model with an optimization model. The simulation model simulated the introduction of paratuberculosis into an importing country through importation of live animals. The model was run for 50000 iterations. Model outputs were the number of imported infected animals and the number of detected infected animals (taking into account the sensitivity and specificity of the test). Two effectiveness parameters were considered: the number of infected animals detected and the net economic benefit. The model either minimized losses or maximized the number of infected animals detected. The optimized parameter was the percentage of tested animals from each imported group. The constraint was the total number of animals sampled (maximum costs for testing). Costs of testing, management costs, and possible costs due to an outbreak were taken into account.

Deterministic simulation models were the most frequently used method in the pests category, used in 22 of the 35 publications. Bogich, Liebhold, and Shea (2008) developed a deterministic simulation model to determine the optimal trap density for an invasive species, the gyspy moth in the United States. Colonies were represented by circular regions, and if the region overlapped, with a survey point, then the colony was detected and eradicated; if it was not detected, it continued to grow. All colonies had to be eradicated at the end of the program. The model could determine the optimal trap density, the minimum total cost (trap costs and eradication costs) for the whole program, and the minimum total cost per year for programs from 1 to 20 years. Examples of deterministic models were also found in the category animal diseases. Boden et al. (2012) compared three control strategies for scrapies using a deterministic transmission model to simulate the within-flock transmission of scrapies for low, medium, and high prevalance flocks. Massaro et al. (2013) used a deterministic simulation model to estimate the transmission of paratuberculosis between cows placed in different states included in the model: heifers, calves, adults, susceptible, exposed, low shedding, and high shedding. Revenues were the slaughter value of the culled animals, the value of the sold animal, and the value of milk produced. Expenditures were the costs for ELISA or EVELISA, the costs of replacing culled animals, and the overhead and operating costs. The model ran for a period of 10 y and compared 3 strategies: no testing, ELISA, or EVELISA. The most cost-efficient surveillance system was the system with the highest average revenue per cow.

Overall, 62% of all models used were stochastic. In the category animal diseases, 80% of the models had at least 1 stochastic variable and stochastic simulation models were common. A Monte Carlo simulation was frequently used to generate random samples from distributions. Values were sampled at random from the input probability distributions. Each combination of input variables was an iteration, hundreds or thousands of iterations were performed to create a probability distribution of the outcome. Scenario-tree models were common stochastic simulation models in the category animal diseases. A flowchart of the disease progression helped to show each step of the process and enabled easy simulation of the effect of different monitoring systems on the outcome. Nodes represented events that had to occur to achieve the outcome and the branches each had a different probability. For example, the JohneSSim model was a stochastic and dynamic simulation model of paratuberculosis within a herd, which simulated the herd dynamics, the disease dynamics within the herd, the control of paratuberculosis, and the economic consequences at herd-level for a period of 20 years (Weber, Groenendaal, van Roermund, & Nielen, 2004). In the category environmental hazards, a stochastic simulation model was used to compare an alternative groundwater monitoring approach with the conventional system. The model simulated the release of a contaminant plume and estimated the detection of the contamination and the size of the plume at detection time. The Monte Carlo approach was used to add uncertainty (Yenigül et al., 2006). In the food safety category, Alban, Rugbjerg, Petersen, and Nielsen (2016) used a scenario tree to evaluate the performance of a monitoring system for the detection of antimicrobial residues. Monte Carlo simulations were used. Finally, in the pests category, Cacho, Spring, Hester, and MacNally (2010) used a stochastic simulation model to simulate the spread of an invasive population and study the interactions between active and passive surveillance.

Assessment of costs

More than half of the selected publications only assessed the monitoring costs. Monitoring and management costs were assessed in approximately one-fifth of the publications The remaining quarter of the publications assessed both costs and benefits using partial budgeting. Examples of management costs were the costs of eradicating the pest, the costs of culling animals, or the costs of tracing back the contamination. A single publication used a partial equilibrium model to analyze the effects of a hazard on the market (Surkov et al., 2009).

Different indicators were used to compare the effectiveness and costs of a monitoring strategy. The benefit–cost ratio (BCR relates the costs of monitoring to the benefits, both of which are expressed in monetary units. In case part or all of the costs and benefits occur in the future, then they should be discounted so that the ratio represents the present value of costs and benefits (Dijkhuizen & Morris, 1997). The net present value (NPV) can be used to measure the profitability of a monitoring strategy, and it represents the difference between the present value of the cash inflows (benefits in monetary units) and the present value of the cash outflows (costs). The future benefits and costs are discounted so that the NPV represents the value of the monitoring program at present (Dijkhuizen & Morris, 1997). If the discount rate is high, a monitoring program with a high initial cost and benefit in the future is penalized, because the money earned today is worth more than money earned in the future. The NPV method was used to assess the monitoring of rinderpest in cattle in Africa. The direct costs of economic losses were compared with the baseline scenario of no intervention. The annual costs and benefits were projected over time and discounted at 12% over a 12-year period to compute the BCR as a measure of economic efficiency and NPV as a measure of economic feasibility (Tambi, Maina, & Mariner, 2004). Tunks et al. (2005) calculated the return on investment for the issue of groundwater contamination: the potential cost savings were divided by the implementation costs of passive diffusion samplers. To calculate a BCR, an NPV, or a return on investment, a partial budgeting approach is required to identify and quantify all the costs and benefits in monetary terms.

The cost-effectiveness ratio relates the total costs of a program, or the costs relative to an alternative solution, to the effectiveness of the program. This ratio is used when the benefits are not easily quantifiable in monetary units (Dijkhuizen, & Morris, 1997). The effectiveness or benefits are not expressed in monetary units but can be measured in different ways. Examples of effectiveness measures include the probability of disease transmission (Häsler, Howe, Di Labio, Schwermer, & Stärk, 2012), the probability to detect disease (Knight-Jones, Hauser, Matthes, & Stark, 2010; Tavornpanich et al., 2008; Tavornpanich, Gardner, Carpenter, Johnson, & Anderson, 2006), or the proportion of correct decisions (Paula-Moraes et al., 2011). The monitoring costs alone are sufficient to calculate a cost-effectiveness ratio.

To conclude, more than half of the publications only assessed the monitoring costs. This is because this approach is straightforward and requires only limited data. Calculating the damages and management costs requires more information than may be readily available. A further explanation may be found in the focus of the authors, as many of the publications were written by groups with a focus on life sciences rather than economics. A partial equilibrium model was only encountered once and was developed by a group specialized in business economics.

Food safety

Few references were found in the food safety category, and all were relatively recent studies. This suggests that cost-effectiveness of monitoring strategies in food safety is only starting to be investigated and more research is needed to improve the cost-effectiveness of current monitoring strategies.

The methods identified in this literature review can be applied to improve research on cost-effective monitoring of hazards in food. We discussed the applicability of the different methods to food safety, based on what was observed in this research as well as the strengths and weaknesses of each method summarized in Table 2.

Since performing experiments with hazards in food safety is neither easy nor ethical to perform, similar to animal diseases, little experimental data will be available or produced. No publications using experimental data were found in this research. Calculated and simulated data will be more applicable to food safety hazards.

Statistical methods are less applicable to food safety. As stated in the previous paragraph, little experimental data will be available. Simulation models, as used in four out of the nine publications, are an appropriate type of model to predict the outcome of different monitoring methods. Simulation models are a way to compare different scenarios and predict outcomes. Optimization models, used in five out of the nine publications, can be used to allocate a budget or to optimize a current monitoring plan. All different ways of solving optimization models, encountered in this research and described in the previous section can be used: genetic algorithms, simulated annealing, linear programming, and SDP. The effectiveness can be optimized for a fixed budget or the costs can be reduced by achieving the same effectiveness at a lower cost. If simulated or calculated data are used, a stochastic model, as used in seven out of the nine publications, is preferred to a deterministic model, because, in that way, uncertainty is included and different ranges of input data can be explored.

With regards to assessing the costs of a monitoring plan, assessing all direct costs and benefits, using partial budgeting seems to be the most comprehensive way of assessing the costs of a monitoring plan. This was however done in only three out of the nine publications. Because the costs and benefits might not be the same for the different stakeholders (farmers, producers, and consumers), multi-criteria decision analysis can be used to help choose between alternative solutions, taking into account preferences of different stakeholders. The stakeholders' interests are represented by weights attached to the criteria used to rate the alternatives. This technique was used by Guo et al. (2014) to optimize the monitoring of swine fever for different stakeholder preferences.

These methods can be applied to mycotoxin monitoring for example: mycotoxin contamination in cereals, fruits, and nuts leads to huge economic losses and potential serious health problems for both humans and animals. Therefore, finding a cost-effective monitoring system is crucial.

Limitations of the search method

This review covered published peer-reviewed primary research papers and published book chapters only; the search did not provide an exhaustive list of methods used in all scientific research. However, by restricting the review to published material, only scientifically validated methods were gathered, which provided a broad overview of the methods in different fields. Only studies written in English were considered. This was considered acceptable because English is widely accepted as the *lingua franca* in science. The search was restricted to references published between January 2000 and December 2016 to provide an overview of the most recent methods, techniques, and applications, thereby capturing the state-of-the-art in these fields. References were searched with keywords. The choice of keywords was crucial to gather relevant studies. Omitting potential synonyms in the search string might have led to missed relevant references. To address this, we added synonyms encountered in the publications of our initial searches.

Conclusion

Our hypothesis that monitoring schemes in the field of food safety rarely include an economic assessment was confirmed by the search results. As the budget allocation available for monitoring is usually limited, it is important to optimize monitoring plans taking into account both costs and effectiveness. In this way, the effectiveness can be optimized for a particular budget or a monitoring scheme can be developed that achieves the same effectiveness at lower cost. The methods encountered in this review can be adapted and used in the field of food safety. Stochastic simulation models, using both historical and simulated data, and optimization models are proven to be suitable. Although used in only a third of the publications encountered in food safety, considering all directs costs and benefits seems to be more comprehensive because the benefits of monitoring, such as an avoided recall of contaminated food placed on the market, can be more important than the costs. A relatively new development that might enrich research on cost-effective monitoring of hazards is the combination of expertise, knowledge, and models from different fields. An example of such interaction is the modeling of zoonoses where plant and animal diseases and food safety all interact and should therefore be modeled together.

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Authors' Contributions

All three authors participated in the design of the study. M. Focker collected the references and wrote the manuscript. H.J. van der Fels-Klerx and A.G.J.M. Oude Lansink performed critical reviews on the manuscript and also wrote texts. All authors read and approved the submitted manuscript.

Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's website:

supporting information

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Appendix

Results of the Systematic Literature Search

Environmental Hazards: soil and water (17 references).

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