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A conceptual model for identification of emerging risks, applied to mycotoxins in wheat-based supply chains

H.J. van der Fels-Klerx[1], M.C. Kandhai[1] and C.J.H. Booij[2]

[1]Wageningen UR, RIKILT- Institute of Food Safety, Unit of Databases, Risk Assessment & Supply Chain Management, P.O. Box 230, 6700 AE Wageningen, the Netherlands; [2]Wageningen UR, PRI-Plant Research International, P.O. Box 16, 6700 AA Wageningen, the Netherlands; Ine.vanderfels@wur.nl

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Abstract

The research described in this paper focuses on identification of the most important indicators for emerging mycotoxins, starting from those produced by *Fusarium* fungi, in wheat-based feed and food supply chains, as well as the development of a conceptual model to predict the occurrence of these emerging toxins, based on the selected indicators. The selection of the most important indicators was based on a literature review and evaluation of the resulting indicators for their relevance. Each indicator selected was appointed to relevant stage(s) of the supply chain to which it is related and, for each indicator, a suggestion for a potential information source is given. The selected indicators cover various influential sectors, amongst others, weather conditions, agronomical practices, trade and legislation, as well as a variety of information sources, e.g. on-farm records and statistical organisations. The conceptual model developed is aimed at predicting the occurrence of emerging mycotoxins – based on the selected indicators – in a particular unit of wheat. The model takes a supply chain approach and can handle various types of indicators and various levels of detail of information on origin of the unit of wheat. The proposed model could be useful in the development of an identification system for emerging risks related to mycotoxins in wheat-based supply chains. Ultimately, such a system will help industry and policy makers in their decision-making process with regard to prevention and control of upcoming risks.

Keywords: emerging risk identification, indicators, risk model, mycotoxins, *Fusarium*

1. Introduction

Wheat-based feed and food supply chains can be contaminated with mycotoxins produced by a variety of fungi, in particular by *Fusarium* species (Köhl *et al.*, 2007). Growth of these fungi and their formation of mycotoxins can occur, depending on the conditions, during various stages of feed and food production, including crop growth, harvest, transport, storage and processing (Beyer *et al.*, 2006). These mycotoxins, e.g. deoxynivalenol (DON), T2-toxin and HT-2 toxin, can cause a variety of adverse health effects in humans and animals, depending on contamination levels in feed and food end products. Due to increased public concern about food safety and its role in international trade, mycotoxins are closely monitored in the European Union (EU) with official regulations (maximum levels) for a variety of mycotoxins in food (European Commission, 2006) and alfatoxin in feed materials (European Commission, 2003). Prevention and control systems, like Hazard Analysis Critical Control Point (HACCP), early warning and predictive models, and advanced diagnostic tools have been developed and implemented by processing industry and food safety authorities in order to minimise the occurrence of mycotoxins (Aldred and Magan, 2004a,b; Magan, 2006).

Several models are available for the prediction of the occurrence of well-known mycotoxins and/or Fusarium

Head Blight (FHB) during primary production (De Wolf *et al.*, 2003; Hooker *et al.*, 2002; Moschini and Fortugno, 1996; Moschini *et al.*, 2001; Rossi *et al.*, 2004; Schaafsma and Hooker, 2006). These models are generally based on statistical relations – as derived from historical data – between the presence of the particular mycotoxin, mainly focusing on DON, or FHB in general, and meteorological and/or agronomical related factors. The well-known example of such a model is DONcast, developed in Canada (Schaafsma and Hooker, 2006), which aims to underpin on-farm decision-making with regard to the use of fungicides such to limit DON contamination at harvest. In addition, first attempts have been made to map predicted contamination of mycotoxin on a regional basis (Battilani *et al.*, 2006; Van der Fels-Klerx and Booij, 2006). Models available are limited to the cultivation period; (post-)harvest conditions are not taken into account. Instead, actual mycotoxin levels are measured at critical (but variable) control points in feed and food supply chains. Also, HACCP systems have been widely introduced by the industry to increase feed and food safety by taking a preventive approach rather than by inspection. Regulation EC/178/2002 ('General Food Law') makes HACCP compulsory for all stages of the food production chain after the primary stage (European Commission, 2002). The merits and effectiveness of HACCP systems for mycotoxin prevention and control has been addressed (Aldred and Magan, 2004a; Aldred and Magan, 2004b). Besides these prevention and control systems, notification or early warning tools, such as RASFF, are used by industry and/or (inter)national authorities. RASFF is a system, established at the European level, for notification of (in)direct risks to human health derived from feed or food (see http://europa.eu.int/comm/food/food/rapidalert/index_en.htm). It is used by national and international control authorities as an effective tool for the exchange of information on food safety problems. Cases in which feed or food safety limits are exceeded, based on results from monitoring and control activities on known food safety hazards, are notified so that immediate actions can be taken by other member states, e.g. with a regional problem such as mycotoxins.

The above-mentioned control and prevention, monitoring and early warning systems provide authorities and industry useful tools to avoid or limit food safety problems. However, unforeseen problems with mycotoxins and other hazards are still occurring due to the influence of new factors and conditions in the supply chain and the environment. Therefore, in addition to the current systems for management of known hazards, it is necessary to broaden the scope with the added aim of identifying new or re-emerging hazards and preventing these hazards from actually becoming a risk. This was recognised by the European Community (EC) and within the framework of the Regulation EC/178/2002, the European Food Safety Authority (EFSA) was assigned the task of setting up a pan-European system for the identification and evaluation of emerging risks with the objective of preventing them (European Commission, 2002). A vision has been developed (Noteborn *et al.*, 2005) for such a system for the identification of emerging risks using a structured and proactive approach. The so-called 'holistic approach' for identification of emerging risks is based upon indicators, derived not only from the food production chain, but also from outside the chain. The set-up of such systems based on indicators is very resource intensive. Therefore, EFSA was advised by its Scientific Committee (SC), as a first step, to limit its work to a number of key areas and focus on the identification and validation of relevant indicators for these areas (European Food Safety Authority, 2006). One of these key areas includes emerging risks related to the occurrence of mycotoxins and, following the SC opinion, these emerging risks were further elaborated upon.

The research presented in this paper focused on identification of the most important indicators for the occurrence of emerging mycotoxins, starting from those produced by *Fusarium* fungi, in wheat-based feed and food supply chains, and potential information sources for the selected indicators. Furthermore, a conceptual model was developed to predict the occurrence of emerging mycotoxins – based on the selected indicators – in a unit of wheat. First, in section 2, background information on the holistic approach is given, and the procedure followed for identification of the most important indicators is explained. Section 3 presents the selected indicators, together with potential information sources, as well as the conceptual model to link the various indicators. Results are discussed and conclusions are drawn in section 4 and 5, respectively.

2. Materials and methods

Background on the holistic approach

This section presents a summary of a structured and proactive approach, called the 'holistic approach', for early identification of emerging risks, as developed in Noteborn *et al.* (2005). An emerging risk (ER) is defined as a feed or food-borne hazard that may in the future present a risk for human health. As risk is a function of hazard and exposure (Codex Alimentarius Commission, 1999), the indication of an ER may relate to (1) a significant exposure to a hazard not recognised earlier, or (2) a new or increased exposure to a known hazard (it is then called re-emerging risk) (European Food Safety Authority, 2006). ER thus may include (1) unidentified new form(s) of a (group of known) hazard(s); (2) poorly characterised hazards; (3) characterised hazards not previously associated with feed or food, or (4) re-emerging hazards and/or new exposure routes. For ER identification, a system or procedure is needed that proactively identifies a potential hazard and prevents it from becoming a risk. Such a proactive system needs more knowledge and information than is available from the feed and food supply chain only. Therefore, the 'holistic approach' (illustrated in Figure 1) must be taken, implying a wide range of disciplines and a variety of different fields of expertise, besides those directly related to the supply chain, to be explored.

First, the fields of interest or 'influential sectors' must be identified, both from inside and outside the supply chain. Thereafter, for each relevant influential sector, one or more critical factors are selected, from which potential indicators for the ER identification system can be drawn. The derivation of indicators from influential sectors and critical factors is illustrated in Figure 2.

An indicator is defined as a signal that indicates the possibility of occurrence of an ER. Indicators may directly be related to one or more stages of a particular feed or food supply chain, or may be connected to the particular (stage of the) chain via one or several links (Noteborn *et al.*, 2005). Information sources must be attached to each indicator to provide an estimation of the level of the particular indicator. The information on indicators may or may not be supplied by or directly related to the feed or food production process themselves.

As an example from the field of mycotoxins, fungal growth and their formation of mycotoxins on cereals can occur during crop cultivation, in particular around flowering. The unforeseen and undesirable contamination of cereal

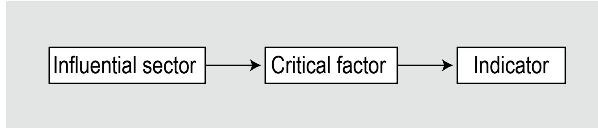

Figure 2. Derivation of indicators in the holistic approach (derived from Noteborn *et al.*, 2005).

products by emerging mycotoxins is affected by factors from various influential sectors. For example, critical factors from the 'environment and energy' and the 'agricultural' sector might be related to meteorological conditions and on-farm agronomical practices, respectively. Rainfall during flowering might be an indicator related to the weather conditions. Weather stations could be the primary information source to supply data on this indicator. For this and other influential sectors, many more critical factors can be identified, however, information on most of the related indicators from historical or technical data will be difficult, or impossible, to obtain. For more information on this holistic approach the reader is referred to Noteborn *et al.* (2005) and/or Noteborn (2006).

Review of indicators and model development

In the course of the European project MYCONET (Van der Fels-Klerx *et al.*, 2007), a case study was performed to select critical factors and most important related indicators for ER identification, as well as potential information sources for the selected indicators. The case focused on emerging risks related to the occurrence of (emerging) mycotoxins, starting with those produced by *Fusarium* species, in European

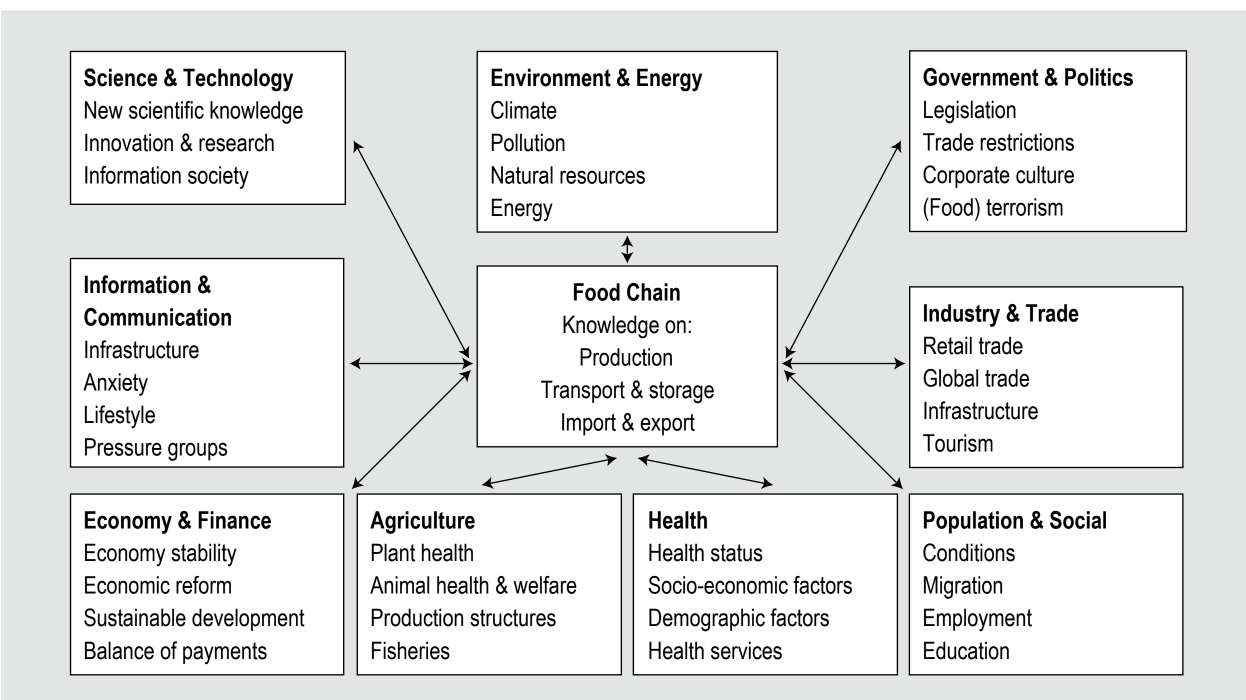

Figure 1. Holistic approach for identification of emerging risks in the feed or food supply chain (derived from Noteborn, 2006).

wheat-based feed and food supply chains. Mycotoxins were chosen as emerging hazards to build upon the foundations from previous studies on ER identification (Noteborn *et al.*, 2005; Noteborn, 2006); wheat was chosen as commodity as this crop covers a large production area in Europe and is an important ingredient for European human food and animal feed production. As *Fusarium* is the most important fungal species occurring in wheat, the case focused particularly on emerging mycotoxins that can be formed by this type of fungi. The spread and persistence of mycotoxins during the various stages of the supply chain are complex. Therefore, indicators were selected for relevant stages of the wheat-based feed and food supply chain, including cultivation, transport and storage, and processing, separately.

For the case study, identification of the most important indicators started by reviewing results from previous related studies (Noteborn, 2006; Park and Bos, 2007; Van Wagenberg *et al.*, 2003). In addition, preliminarily results (not published yet) from the SAFEFOODS project (see http://www.safefoods.nl) were obtained for the current purpose. All (critical) factors and potential indicators mentioned in these studies were evaluated for their relevance, and the most important ones (for the current case) were identified. Next, the selected indicators were appointed to relevant stage(s) of the wheat-based supply chain and potential information sources were suggested for the majority of the indicators.

Subsequently, a conceptual statistical model was developed to predict the occurrence of emerging mycotoxins in a (particular) unit of wheat, applying a supply chain approach and based on the selected indicators. Given the variety in the nature of the selected indicators and in the level of detail of information available, the model focused especially on taking into account these characteristics of indicators in an ER identification system.

3. Results

Indicators for emerging mycotoxins in the wheat-based supply chain

The focus of the reviewed studies differed slightly, as well as the methods used to identify potential indicators. In Van Wagenberg *et al.* (2003) the focus was on early identification of increasing DON levels (a re-emerging risk related to a known hazard) in the wheat-based supply chain, based on predictive factors. Indicators were identified by a literature review, followed by a series of individual in-depth interviews with 5 experts. In total 28 indicators were selected as being related to wheat cultivation (21 indicators) and storage (7 indicators). In Park and Bos (2007) critical factors and indicators for mycotoxin risks were identified by analysing mycotoxin prevention tools, existing early warning systems, mycotoxicosis case studies and other sources. In total 16 indicators were identified for the presence of mycotoxins in cereals. In Noteborn (2006) potential indicators for emerging risks were identified by retrospective evaluation of various historic incidents, including an outbreak of aflatoxicosis. Initially, in total 270 indicators were identified. In two consecutive workshops, this list was reduced to general indicators, e.g. temperature and plant-related stress factors, and potential information sources were identified. Specific indicators applicable to mycotoxins were mainly related to crop cultivation, transport and storage. Within SAFEFOODS indicators were identified for prediction of the occurrence of re-emerging known mycotoxins (not further specified) for each of three commodities, including wheat. The main indicators were identified by a total of 13 in-depth interviews with 17 experts (4 interviews were held with 2 experts at the same time). After the interviews, each individual expert was asked to grade the relative importance of the indicators he/she had identified in one of four categories (from unimportant to highly important). The final list included 21 most frequently mentioned indicators, derived from various influential sectors, not specified to a stage of the supply chain.

The results of the current review are presented in Table 1, including critical factors and most important related indicators, per stage of the chain, for the occurrence of emerging mycotoxins in European wheat-based supply chains, as well as suggestions for potential information sources. As can be seen from this table, selected indicators related to the critical factor 'agronomical practices' all are linked to one stage of the supply chain (cultivation), whereas the majority of the other critical factors and related indicators applies to more than one stage of the chain. In addition, information on the indicators related to the cultivation system must mainly be obtained from farmers' records, whereas information on most of the other indicators can be derived from other sources.

Information model

The selected indicators vary in their type and the range of values they can take (see Table 1). In this regard, they may be classified as quantitative or qualitative indicators. A quantitative indicator can be expressed as a numerical quantity defined by its mean and range. Examples of such indicators related to 'biobased economy' might be the 'percent of land covered by energy crop' and 'prices'. Qualitative indicators cannot be expressed as a number, but can be put into classes with levels. An example of a qualitative indicator, related to 'agronomical practices', is 'tillage practice', which might include the three levels of 'deep-ploughing', 'intermediate ploughing' and 'no-tillage'.

The (estimated) impact of the various indicators on the occurrence of emerging mycotoxins, expressed in their

Table 1. Critical factors and selected most important indicators, together with suggested potential information sources, for identification of emerging mycotoxins in wheat-based supply chains.

Critical factor	Indicator	Stage of the wheat-based supply chain			Potential information source (suggested)
		Cultivation	Transport & storage	Processing	
Weather conditions	Temperature	X	X		Meteorological institutions
	Relative humidity/rainfall	X	X	X	Management system, meteorological institutions
	Water activity in kernels	X	X	X	Management system
Agronomical practices	Crop rotation	X			Farm management system
	Crop variety	X			Farm management system
	Pesticide/fungicide use	X			Farm management system
	Spraying technology	X			Farm management system
	Decontamination of seeds	X			Farm management system
	Weed management	X			Farm management system
	Sowing density	X			Farm management system
	Use of growth inhibitors	X			Farm management system
	Lodging	X			Farm management system
	Fertilization	X			Farm management system
	Regional infection pressure	X			Farm management system
	Tillage/soil management	X			Farm management system
	Yield (per ha)	X			Statistical organization, farm management system
	Irrigation and drainage	X			Farm management system
	Plant stress factors	X			Farm management system
	Harvest logistics/delay	X	X		Farm management system
Biobased economy	Land (%) covered by cereal energy crops	X			Statistical organization
	Price levels for energy and food cereals		X	X	Statistical organization
Innovation & technology	Level of technology used	X	X	X	Statistical organization
	Awareness of food safety	X	X	X	Scientific reports
	Communication/trust between parties	X	X	X	To be identified
	Knowledge dissimination	X	X	X	Farmers and industry organizations
	Ventilation/storage technology		X	X	To be identified
Quality & safety control	Grain quality		X	X	Registration systems
	Traceability and quality systems	X	X	X	To be identified
	Certified crop management	X			EUREP-GAP
	Storage capacity and logistics		X	X	European commission
	Transport duration and distance		X	X	Business intelligence reports
	Carry-over of contamination	X	X	X	Management system
	Blending/mixing		X	X	Local authorities, management system
Trade	Trade agreements			X	European commission
	Index of trade partners and trade volumes		X	X	European commission
	No.products passing through national borders with and without inspection		X	X	Customs and excise information
	Foreign control of enterprises	X	X	X	World Trade Organisation
	International trade balance		X	X	EUROSTAT, Business journals
	Price premiums			X	World bank, EU trace system
	Regional food shortage	X		X	Food and Agriculture Organization

Table 1. Continued.

Critical factor	Indicator	Stage of the wheat-based supply chain			Potential information source (suggested)
		Cultivation	Transport & storage	Processing	
Legislation	Compliance with rules and regulation	X	X	X	To be identified
	National and EU legislation		X	X	European commission, national ministeries
Consumption	Consumption patterns	X	X	X	Food and consumer surveys
	Food innovations	X	X	X	To be identified
	Exotification	X	X	X	To be identified
Research	Technology push	X	X	X	To be identified
	New/improved detection methods for mycotoxins	X	X	X	Scientific journals, pattents
	Influence of science on production & legislation	X	X	X	To be identified
	Changes in composition of fungal populations	X	X	X	Scientific reports, datasets
	Outbreaks/measurements of defined species	X			Scientific reports, datasets

predictive value, will vary according to their relative contribution in a particular setting. The predictive value of a particular indicator represents the increase in the (estimated) occurrence of emerging mycotoxins by an increase in the specific indicator. In fact, this increase is affected by two factors, being the (statistical) relationship between the particular indicator and the occurrence of emerging mycotoxins, and the relative importance of the particular indicator in comparison to other relevant indicators. Besides the individual indicators, relevant interactions between indicators also need to be taken into account. This is because, due to synergistic effects, an increase in the level of two low-impact indicators may have more effect then a high level of one high-impact indicator. The relationships between indicators and the predicted occurrence of emerging mycotoxins in a particular stage of the wheat-based supply chain can be approximated statistically, in case of two indicators, by the following additive model:

$$Y_{l,m,s} = (\alpha_{l,m,s} \times x_{s,1}) + (\beta_{l,m,s} \times x_{s,2}) + (c_{l,m,s} \times x_{s,1} x_{s,2}) + E_{l,m,s} \qquad (1)$$

Where:

$Y_{l,m,s}$: the occurrence (possibly after suitable data transformation) of emerging mycotoxins in a unit of wheat in stage s of the supply chain, with information on location and time of the unit being available at the level l and m, respectively

l: level of detail of information available on location of the unit (with l = 1, 2, …, L; and with L being the most detailed level applicable)

m: level of detail of information available on time of the unit (with m = 1, 2, …, M; and with M being the most detailed level applicable)

s: stage of the wheat-based supply chain (with s = 1, 2, …, S; and with S being the total number of stages in the supply chain; e.g. 1= cultivation; 2= transport, 3=storage, 4=processing)

$x_{s,n}$: level of indicator n (with n – in this case – being 1 or 2) in stage s

$\alpha_{l,m,s}$, $\beta_{l,m,s}$, $c_{l,m,s}$: regression coefficients (predicted values) for the main effect of indicators $x_{s,n}$ (with n – in this case – being 1 or 2) or an interaction term, given information on location and time of the unit is available at level l and m, respectively

$E_{l,m,s}$: error variable for the estimated occurrence of emerging mycotoxins

Equation 1 illustrates the relationship for two indicators. When more indicators are used in an ER identification system all relevant indicators and interaction terms should be taken into account. As the selected indicators could vary between the different stages of the chain they are – either directly or indirectly – linked to (see Table 1), Equation (1) needs to be further defined, per stage s of the supply chain, by identification of the relevant indicators and interaction terms, and an estimation of their predictive values. In principle, the occurrence of emerging mycotoxins in any consecutive stage of the wheat-based supply chain after harvest, depends – to some extent – on the (estimated) occurrence in one or more of the previous stages. This can be written as:

$$Y_s = f(Y_s, Y_{s-1}, \dots, Y_{s-S+1}) \quad (2)$$

With:

Y_s: occurrence of emerging mycotoxins in a unit of wheat in stage s of the supply chain

s: stage of the wheat-based supply chain (with $s = 1, 2, \dots$, S; and with S being the total number of stages of the supply chain)

The model (in particular Equation 2) should be adapted to the fact that the prediction unit, in this case the unit of wheat, varies in relation to the stages of the supply chain. This is due to mixing and splitting of units throughout stages of the supply chain and related production processes. For example, the unit may vary from a batch at the farming field level, via trading lots, up to shipping volumes. This may complicate the calculations as figures have to be combined and different information sources are needed according to the purpose.

The application of Equation 1 in predicting the occurrence of emerging mycotoxins in a particular unit of wheat, in a certain stage of the supply chain, starts with further definition of the unit, e.g. a batch, and identification of the stage of the chain the unit is in. Suppose, the unit is a batch of wheat derived from one field of a farmer. The position of the batch with regard to location and time, and possibly also its history, must be known in order to estimate the levels of the particular indicators, together with their predictive values, in the model. The next step is to identify the extent to which this information on origin (location and time) is available for each of the indicators (and related information sources). E.g. in the trade stage, the grower of the batch of wheat, the field the batch is derived from, and date of harvest may be exactly known; on the other hand, the only information available might be that the particular batch comes from Northern America and is harvested in a particular year. In the first case, information on amount of rainfall and temperature around flowering, two potential indicators, can be derived from weather institutes – in particular in case the geographical coordinates of the field are exactly known, whereas, this is not possible in the second case. Note that indicators that can be estimated visually or measured on the batch quickly (e.g. kernel size) are independent of the level of detail of information on origin available and, in principle, can always be estimated. Overall, for a given indicator, for a particular unit of wheat in a particular stage of the supply chain, a certain level of detail of information on position and history with regard to location and time of the unit will be available, varying from not known at all to exactly known at the most detailed level possible. Theoretically, each combination of levels of detail of location and time is possible, depending on the definition used for the unit. The level of detail of information available will affect the precision of the regression coefficients (predictive values) of the indicators in the model and, herewith, also of the estimated occurrence of emerging mycotoxins. The relationship between the available information on origin (location and time) of units of wheat and the precision of the predictive value of the particular indicator is illustrated in Figure 3, with examples of levels for location (l) and time (m) for a batch of wheat in the cultivation stage (s=1).

From Figure 3 it can be seen that an indicator for the occurrence of emerging mycotoxins in a unit of wheat, in a particular stage of the supply chain, can be appointed to a cell (l,m) in the matrix depending on the level of detail of information on origin of the unit available. The level of detail of the available information increases from the left upper corner to the right bottom corner in the matrix. In the left upper cell of the matrix, there is no information

		Level of detail time (*m*) →				
	Stage of chain (s)	**1) Not known**	**2) Year**	**3) Month**	**4) Week**	**5) Day**
↓ Level of detail location (*l*)	**1) Not known**	...	...	...	...	...
	2) Continent	...	...	...	...	...
	3) Country	...	...	...	...	...
	4) Region	...	...	...	...	...
	5) Town	...	$\alpha_{5,2,1}$	...	...	...
	6) Farm	...	...	...	...	$\alpha_{l,m,s}$

Figure 3. Relationship between the available information on origin (location and time) of units of wheat and precision of the predictive value of the particular indicator, illustrated with levels for location and time for a batch of wheat (derived from a field from one farm) in the cultivation stage (s=1) (derived from Van Wagenberg *et al.*, 2003). With

$\alpha_{l,m,s}$: regression coefficient for a given indicator with information available on origin of a batch of wheat being at level l for its location and level *m* for time with, in the case of this example, *l* = 1,..,6 and *m* = 1,..,5;

$\alpha_{5,2,1}$: predicted value for a given indicator in the model for the cultivation stage with information on the unit of wheat being available at the town level (location being at level 5) at the yearly basis (time being at level 2).

available on location and time of the unit, whereas in the right bottom cell, this information is exactly known at the most detailed level. The principle presented in Figure 3, and illustrated for the cultivation stage, is not restricted to (this) one stage of the supply chain; it applies to all consecutive stages of the chain as well. For each stage, the particular indicators will vary in the level of detail of available information on location of the unit of wheat (where the unit is stored, where it is processed) and time (when it was stored, when it is processed, etc.). Therefore, the dimensions of location and time of the particular unit of wheat need to be defined, per stage, and levels or values of the indicators must be appointed given the particular level of information on origin available. This level of detail will define the possibility and accurateness of the estimation of the predictive values of the indicators in the model and, hereby, also of the overall predicted occurrence of emerging mycotoxins in the unit of wheat. Thus, when information on the origin of the unit of wheat is available at the most detailed level applicable for all indicators in the model, estimations of the predictive values – in principle – are most accurate. However, the accuracy also depends on the quality of the information (source) on the indicator available. The most detailed level applicable to a particular indicator depends on the definitions used for the unit of wheat and the indicator themselves. For a given unit of wheat, the applicable level of detail may vary between the indicators. For example, for the indicator 'percentage of land covered by energy crops', information on location will be needed at the country level, which is much less detailed than the information needed for the indicator 'amount of rainfall during cultivation', preferably being available on the farm field level.

4. Discussion

Indicators and information sources

The selected indicators for the occurrence of emerging mycotoxins are obtained from inside the wheat-based supply chain as well as from outside the chain (see Table 1). Information on indicators directly related to feed and food production can often be obtained from registration of the particular organisation in the chain, e.g. using on-farm management systems. The availability and the quality of the information may depend on the extent to which quality management systems and certificates are used. Sometimes, the necessary information on a highly important indicator, although perfectly accessible and of high quality, might be confidential and not open for public use. In that case, the use of information from next best sources or on indicators of secondary importance would be the only option. Information on indicators from outside the production chain, e.g. from statistical organisations like EUROSTAT (see http://ec.europa.eu/eurostat) or weather stations, is often of a less confidential nature and, hence, could be more easily obtained. Overall, the aspect of the availability and quality of information sources should be considered well in the further selection of indicators for an identification system for emerging mycotoxins.

Information model

The statistical information model presented in this paper forms the basic concept of linking indicators, for various stages of the chain, to predict the occurrence of emerging mycotoxins in the wheat-based supply chain. Although the conceptual model is developed for the case of emerging mycotoxins, its principle holds for other types of emerging hazards as well. As such, it provides a generic concept for an ER identification system for the occurrence of any other type of emerging hazard. The research described identified critical factors and most important related indicators for the occurrence of emerging mycotoxins, mainly produced by *Fusarium* fungi. Indicators have been identified per stage of the wheat-based supply chain, and suggestions for potential information sources have been made. With this, the research presented in this paper, builds on the foundations of ER identification previously laid down (Mengelers, 2005; Noteborn *et al.*, 2005; Noteborn, 2006; Park and Bos, 2007), and provides a step forward in the development of a functional system for ER identification of emerging mycotoxins in the wheat-based supply chain. A next step in the development of such a system might involve more precise definition of the selected indicators, preferably in a quantitative and predictive way. For a particular indicator, predictive values and their ranges might be known – to a greater or lesser extent – or might be completely uncertain. In an ER identification system for the occurrence of emerging known mycotoxins, regression coefficients for part of the indicators – particularly for those related to agronomical and weather-related factors – can be derived from (historical) datasets. It is particularly useful to statistically analyse large and long-term monitoring datasets in order to estimate the relationship between the particular indicator and the occurrence of known mycotoxins, such as has been done previously, e.g. by Hooker *et al.* (2002). Predictive values on indicators from other influential sectors are less likely to be available or to be obtained in the short term, and will – in the most ideal situation – be best guesses. For an ER identification system for really new or little known emerging hazards, the entire model will have a more qualitative character and expert estimates on the predictive values need to be used, as historical information (per definition) is not available for all the indicators.

The conceptual model developed can take into account various levels of accuracy of the estimated predictive values (from datasets, experts) of the indicators, as well as the variety in the nature of indicators and level of detail of information available on these indicators. This conceptual model could be applied using Bayesian methods, as this statistical technique can handle various levels of hierarchy. In addition, using Bayesian methods will also provide the possibility of using a-priori knowledge. Bayesian methods are based on a principle, known as Bayes' theorem, for combining data (observable quantities) with prior information on the parameters of a model (unobservable quantities) (Gosh *et al.*, 2006). Specifically, the fundamental steps of a Bayesian method are: (1) formulating a probability model for the data given the model parameters (termed the likelihood); (2) formulating a prior distribution for the model parameters; and (3) combining the prior distribution and the likelihood to calculate the posterior distribution of the parameters. Bayesian methods are especially suited to hierarchical models where the basic observations are thought to come from distributions with parameters that are themselves again modelled as coming from a higher-level distribution. So, for example, data on a national level could be used to formulate a prior distribution to be used together with observed data on the farm scale.

Another step in the development of a functional ER identification system for emerging mycotoxins is to clearly define the aims and conditions for its application in practice. As it is foreseen that these aims and conditions will vary among specific groups of users, such as industry or authorities, they must be defined for each of these groups separately. E.g. national inspection authorities might want to focus their border inspection activities depending on the expected occurrence of mycotoxins in particular units of wheat upon arrival. On the other hand, industry might want to use an ER identification system to underpin decision-making on buying and processing of units. Also, the format of the model outcome that will be provided to the particular user – in this case being the estimated occurrence of emerging mycotoxins – must be clearly defined. Risk managers might want to obtain the overall model outcome of the predicted occurrence, taking into account all indicators at the same time, or a signal to base their decisions upon in case this model outcome exceeds a certain pre-set level. On the other hand, they also might want to know the level of each indicator in the model, together with its relative contribution to the overall predicted occurrence of the emerging mycotoxins. In the last case, they may want to use this insight into the 'derivation of the final estimated occurrence', in combination with their own knowledge and expertise, to arrive at a final decision.

5. Conclusion

This paper presents the most important indicators for identification of emerging risks related to mycotoxins in the wheat-based feed and food supply chain, as well as a conceptual model to predict the occurrence of emerging mycotoxins, based on the selected indicators. The proposed model could be used to integrate information on various types of indicators and various levels of detail of information available on the specific indicators. Although developed for the case of emerging risks related to mycotoxins, it provides a generic approach that can be applied to emerging hazards as well. The selected indicators and the proposed information model provide keystones for the development of a functional ER identification system related to emerging mycotoxins in the wheat-based feed and food supply chain. Ultimately, such a functional ER identification system will provide industry and policy makers with an early signal for the potential occurrence of emerging mycotoxins, and will hereby underpin their decision-making process with regard to the control of the upcoming mycotoxin hazard so as to prevent it from becoming a risk or even a food safety crises.

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