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Review

Proactive systems for early warning of potential impacts of natural disasters on food safety: Climate-change-induced extreme events as case in point

Hans J.P. Marvin [a,*], Gijs A. Kleter [a], H.J. (Ine) Van der Fels-Klerx [a], Maryvon Y. Noordam [a], Eelco Franz [b], Don J.M. Willems [c], Alistair Boxall [d]

[a] RIKILT Wageningen UR, P.O Box 230, 6700 AE Wageningen, The Netherlands
[b] RIVM – Centre for Infectious Disease Control, P.O. Box 1, 3720 BA, Bilthoven, The Netherlands
[c] Food and Biobased Research, Wageningen University and Research Centre, P.O. Box 17, 6700 AA Wageningen, The Netherlands
[d] Environment Department, University of York, Heslington, York YO10 5DD, United Kingdom

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A B S T R A C T

According to a recent report of the Intergovernmental Panel on Climate Change, the frequency of certain climate extremes is expected to increase under the influence of climate change. This review presents potential direct and indirect effects of such extremes as well as other severe weather and hydro-meteorological events on the occurrence of hazards in food produced by various agricultural systems. In addition, we review the applicability of early warning systems to warn of the development of food safety hazards induced by natural disasters, with climate-change-induced extreme events as case in point. Monitoring systems focused on food safety hazards may miss - or pick up with delay - the occurrence of new hazards or known hazards in food products in which they previously did not occur. We conclude that, by better use of the available information (being plant-, animal-, human disease-focused systems monitoring weather and other environmental conditions and/or systems collecting publications on the internet), the negative impact of severe natural events on food safety can be minimized.

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* Corresponding author. Tel.: +31 317 480342; fax: +31 317 417717.
E-mail address: hans.marvin@wur.nl (H.J.P. Marvin).

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1. Introduction

Food safety problems may arise as a consequence of exposure of humans to chemicals or pathogens contaminating agricultural products (*e.g.,* crops, livestock, and fish) or drinking water. The likelihood of development of food safety problems will vary by agricultural sector and will depend on the level of organization, food safety control systems, environmental awareness and adaptation capacity within a particular system.

In this paper, we will focus on well-developed global and Western (European, USA) early warning systems, and verify whether these systems are able to timely detect (directly or indirectly) food safety hazards linked to extreme weather and other hydro-meteorological natural events as case in point. We will describe examples of severe hydro-meteorological events that may impact the safety of agricultural produces and discuss the various types of early warning systems for food safety hazards that are in place. It is important to be aware of these weather-extreme-linked food safety effects because the ability and capability to mitigate on these problems may not be equally developed all over the world and globalisation of our food supply makes that contaminated food/feed stuff can move rapidly around the world.

2. Food safety risks driven by climate extremes, and other severe weather and hydro-meteorological events and natural disasters

It goes without saying that natural extreme events and disasters can have an immense and long-lasting impact on the livelihood of individuals, communities, and the environment at large. Such natural events can be classified as hydro-meteorological and geophysical events. Agriculture is a sector that is particularly vulnerable to environmental changes. Hydro-meteorological events that can affect agricultural land, pastures, and forests include drought, heat waves, floods, tropical storms (cyclone, hurricane, typhoons), forest fires, and landslides, and also insect infestations, among other things. A major process that is considered to be driving the occurrence of such environmental, hydro-meteorological events is climate change. A recent report of the Intergovernmental Panel on Climate Change (IPCC) reports on climate extremes, their potential impacts on society, and the mitigation strategies for these effects (IPCC, 2012).

Besides its impact on agricultural systems and food security, climate change is also considered to have an impact on food safety (Miraglia et al. 2009; Tirado, Clarke, Jaykus, McQuatters-Gollop, & Frank, 2010; Tubiello et al., 2008). Through higher temperatures, elevated CO_2 concentrations, precipitation changes and extremes, increased pest and weed pressure and increased vulnerability of organic carbon pools, food production systems will be affected but the effects will vary for the different regions in the world (Tubiello et al., 2008). The overall trends in climatic conditions may allow for the prediction of long-term impacts on agricultural production and allow risk managers and policy makers to make decisions well in advance so as to prevent or mitigate any adverse impacts on mankind and the environment in a timely manner. In contrast, short-lived and sudden extreme hydro-meteorological events may be more difficult to cope with in terms of the ability to predict such irregular events on a short-term basis and to contain the associated risks. This also holds true for other, geophysical natural events and disasters such as earthquakes, tsunamis, and volcano eruptions. Risk managers responsible for maintaining the safety of our food supply would therefore benefit from a timely warning of event-associated hazards and risks for food safety, so that measures can be taken to mitigate these risks.

3. Examples of severe hydro-meteorological events potentially impacting on the safety of produce from agriculture and fisheries

Sivakumar (2008) provides an overview of the various hydro-meteorological disasters affecting agriculture, as well as pastures (rangeland) and forestry, which include the following: Landslides and avalanches; droughts and famines; extreme temperatures and heat waves; floods; hurricanes; windstorms; forest/scrub fires, and others. Below and summarized in Table 1, we will give a number of historic examples of these events and how specific ones impacted on the safety of foods at various stages of the agriculture and fisheries production chains. Other natural disasters besides these hydro-meteorological events include geophysical events not further discussed here, such as volcanism, earthquakes and tsunamis. It has recently been postulated that various climate-change-related events may also indirectly lead to an increased frequency of such events. For example, the melting of ice-masses of ice-covered lands (experiencing less downward pressure) could lead to uprising of the landmasses and subsequently to earthquakes and tsunamis (McGuire, 2012).

3.1. Land- and mudslides

A landslide is the gravity-induced movement, from a slope downward, of land, rock, and debris, while a mudslide specifically refers to the movement of mud. Land- and mudslides can vary widely in size of the volume and depth, as well as the speed of the movement. It is particularly the fast and sudden kind of landslides that are of concern for the topic of this article. A wide range of causes can trigger landslides, including both natural ones, such as heavy rainfall and earthquakes, and others related to human activity, such as the technical failure of dams or the loading of slopes with constructions. While inland areas with mountains, hills, and slopes may be prone to the dangers of landslides, this also holds true for coastal and submarine cliff areas, where landslides could give rise to tsunamis. Avalanches, involving snow and ice, are related to this category of events and commonly treated within the same bracket (JRC, 2012; Sivakumar, 2008). The IPCC concluded that there is high confidence that changes in heavy precipitation will affect landslides in some regions of the globe, while this also holds true for certain high mountain phenomena (slope instabilities, mass movements, glacial lake outbursts) as caused by heat waves, glacial retreats, and/or permafrost degradation (IPCC, 2012).

Recent examples of mudslides of particular interest to food safety hazards include those involving the movement of toxic-contaminant-containing masses, such as tailings containing cyanide and heavy or other toxic metal species derived from mining

Table 1
Examples of hazards and risks to the safety of products produced by the agricultural and fisheries sectors imposed by climate extremes and other severe weather and hydro-meteorological events.

Event	Objects targeted	Hazard	Risk	Historic example(s)
Land- and mudslides	Landfill, mine tips, tailings dams	Contamination of surface water and agricultural land with contaminants contained/deposited by the masses (*e.g.,* mud) released by the slide	Contamination of water organisms used as food, crops grown on contaminated soils	Baia Mara (Romania) tailings dam failure in 2000, leading to release of large quantities of cyanide and heavy metals into local waterways and a major European river (Cunningham, 2005)
Drought	Crops infected with moulds, water reservoirs	Stressful conditions leading to aflatoxin formation by moulds; concentration of contaminants and pathogens in surface water	Contamination of harvested crop commodity with aflatoxins; contamination of irrigated crop or caught fish	Aflatoxin contaminationof maize in Eastern Kenya in droughtful years (Daniel et al., 2011); increased contaminant loads in a US lake serving as drinking water reservoir (Benotti, Stanford, & Snyder, 2010)
Heat waves	Crops infected pre-harvest with moulds	Combination of high temperatures and either drought or humidity that favour aflatoxin and ochratoxin A formation in crops	Contamination of harvested crop commodity with aflatoxins and ochratoxin A	Infection of maize in Northern Italy with *Aspergillus flavus* and aflatoxins following a heat wave in 2003 (Giorni, Magan, Pietri, Bertuzzi, & Battilani, 2007)
Floods	Agricultural lands in flood plains	Flood water containing pathogens and contaminants that are deposited on the flooded land after retraction of the water	Contamination of crops consumed by humans and animals; and of pastures used for grazing; infection of food-producing animals with zoonotic pathogens	Higher levels of heavy metals in flood deposits on agricultural land than in the underlying soil following river flooding (Albering, Van Leusen, Moonen, Hoogewerff, & Kleinjans, 1999)
Heavy precipitation	Seafood organisms and irrigated crops	Contact with freshwater containing runoff with pathogens, contaminants and nutrients, caused by heavy precipitation	Contamination of irrigated crops with pathogens and contaminants; infection of seafood-producing organisms with human pathogens; stimulation of harmful algal blooms or cyanobacteria by nutrients	Increased likelihood of contamination of mussels (used as indicator organisms) with *Cryptosporidium* in Californian coastal waters following heavy precipitation a week before sampling (Miller et al., 2005)
Tropical storms	Crops and animals grazing on pastures in areas flooded by storm surge	Deposits from the storm surge may contain pathogens and contaminants	Contamination of crops and products derived from livestock residing in the flooded areas	Increased levels of pathogens and contaminants in areas flooded after hurricane Katrina (Abel et al. 2010; Fox, Chari, Resnick, & Burke, 2009; Presley et al., 2006; Rotkin-Ellman, Solomon, Gonzales, Agwaramgbo, & Mielke, 2010)

operations. The release of these masses into waterways could pose a toxic hazard to wildlife (as well as to consumers of food products from aquatic species living in these waters), drinking and irrigation water, while residue remaining on agricultural fields could pose a hazard for the crops grown or for animals grazing there. The example featured in the table is that of Baia Mara, while certain other historic events are the breakage of a dam retaining mud containing heavy metals near Aznalcollar in Spain in 1998, and the Ajka alumina sludge spill in Hungary in 2010.

In the case of Baia Mara, the solution containing mining waste ("tailings") remaining after extraction of precious metals with cyanide was allowed to settle in a pond while the solution was being recycled for re-use in a closed system (*i.e.,* without discharge into the environment). During the accident, the dam of the pond, which consisted of the sediment of previous recycling steps held back by a plastic lining, failed due to stress caused by unusually heavy rainfall leading to a large quantity of water accumulating in the pond. The dam breakage and the subsequent release of the contaminated pond's contents into the local waterways and subsequently the Danube, a major European waterway, was accompanied by contamination of these waterways with high cyanide levels and heavy metals, causing extensive damage to wildlife (Cunningham, 2005).

Various initiatives at the national, regional, and global level monitor for the occurrence of land- and mudslides, and/or their mitigation, such as the International Consortium on Landslides, which brings together researchers, and various databases, such as that of the US Geological Survey and the GLIDE disaster database.

3.2. Drought

With regard to droughts, the IPCC concluded that there is medium confidence that droughts will intensify in the 21st century as caused by decreased rainfall or increased evapotranspiration, for certain regions in the world, *i.e.*, Southern and Central Europe, the Mediterranean, North and Central America, Mexico, Northeast Brazil, and Southern Africa (IPCC, 2012). While drought is likely to affect food security, such as for rain-fed agriculture, also impacts on various food safety parameters can be envisaged. The examples featured in Table 1 include the impact of drought on aflatoxins in maize in Kenya, in regions particularly affected by aflatoxicosis. The authors (Daniel et al., 2011) carried out a 3-year study among households, which mainly relied on home-grown maize. It thus showed that in two years of the study, aflatoxin levels were high in many of the samples, while they were substantially less in the third year. The authors related this discrepancy to the likely impact of drought stress in maize in the two first years on the contamination with aflatoxins (Daniel et al., 2011). Another drought-related phenomenon with potential implications for the safety of agricultural and fisheries products is when decreased levels of waterways, lakes and other reservoirs lead to increased levels of contaminants after mixing with wastewater streams discharged from wastewater treatment facilities (*e.g.,* Benotti et al., 2010).

Examples of initiatives that focus on droughts include the European Commission's Joint Research Center's European Drought Observatory focussing on the situation in European countries, and the Food and Agricultural Organization's Global Information and Early Warning System, both employing satellite imagery. The North American Drought Monitor is another example of a transnational collaboration (between USA, Canada, and Mexico), focussing on the droughty conditions affecting Northern America, a summary of which can be downloaded in the form of geographical maps from this initiative's website. The GLIDE disaster database also features reports on drought in the different countries around the world.

3.3. Heat waves

In its report on climate extremes, the IPCC concludes that it is virtually certain that, at a global scale, increases will occur in the frequency and magnitude of warm daily temperature extremes, while cold extremes are to decrease. For heat waves over most land areas, it also concludes that it is very likely that their length, frequency, and/or intensity will increase.

Particularly known for their dependence on temperature and humidity within the pre-harvest time intervals of crop flowering and seed formation are moulds that grow on crops and are capable of forming mycotoxins. In their review on the possible linkage between climate change and mycotoxins, Paterson and Lima (2011) mention the formation of aflatoxins (by *Aspergillus flavus*) and ochratoxin A (by *Aspergillus ochraceus*) being favoured by higher temperatures (*e.g.*, towards 30 °C) if combined with droughty and humid conditions, respectively. These authors also reason that when the temperature is to rise further, the aflatoxin-producing moulds will out-compete the ochratoxin-forming ones on the same crop (Paterson and Lima, 2011). The example in Table 1 features the unprecedented infection of maize in Northern Italy with *A. flavus* and subsequently the high level of aflatoxin contamination of maize-derived feeds following a heat wave there in 2003. This, in turn, led to higher contamination of milk with aflatoxin M1, a metabolite formed by cows, from animals fed diets containing the contaminated maize (Giorni et al., 2007).

Another example of a food safety hazard known to be influenced by higher temperatures is more favourable conditions for the growth of certain microbial pathogens (*e.g., Salmonella spp., Escherichia coli*) such as in the environment of fish (seawater) and agricultural organisms, and further down the production chain in foods kept at ambient temperatures, potentially leading to increased numbers of food poisoning (reviewed by Boxall et al., 2009; Miraglia et al., 2009). Higher temperatures may also lead to changes in consumer behaviour with altered exposure scenarios as a consequence, such as food choice and processing (*e.g.,* barbecue). A study on the occurrence of the number of food-borne illnesses caused by various microbial pathogens in England and Wales show that while there is a positive correlation between such illnesses and the ambient temperatures in the period (up to five weeks) preceding the report of the illness, this factor has become less important since the 1990s, indicating that certain preventive measures are successfully being implemented (Lake et al., 2009).

An example of initiatives monitoring for the possible occurrence of heat waves is the EUROHEAT project, which has developed an online climate information decision support tool for heat in Europe, with maps highlighting the areas that are prone to predicted risk of heat waves. EUROHEAT is a joint collaboration between the World Health Organization's regional Office for Europe and the European Commission's Directorate-General for Health and Consumers.

3.4. Floods

Floods can either be the overflowing of natural waterways (such as rivers) beyond their natural capacities or the submersion of areas (*e.g.,* cities) that are not normally submerged. Various causes of flooding may exist, such as heavy precipitation, melting of snow or glaciers, and failure of dams retaining water reservoirs. The IPCC report on climate extremes states that there is limited to medium evidence for the impact of climate change on the magnitude and frequency of flooding at the regional scale given the limited technical facilities to monitor these events and some additional confounding factors (*e.g.,* man-made changes to riverine systems such as dam construction). For example, the report notes that there is evidence indicating that increasing temperatures have led to earlier melting of snow in mountainous areas feeding rivers during the spring season hence leading to an earlier appearance of annual peaks in the flow of these rivers. This does not necessarily indicate, however, a greater magnitude of this annual peak flow, particularly given that climate change may also lead to decreased snowfall before melting occurs. Given this limited evidence and the low agreement between experts on this issue, there is low confidence overall on the relationship between climate change and fluvial floodings. Yet based on physical reasoning, there is medium confidence that heavy precipitation will lead to rain-caused flooding in certain catchment areas or regions (IPCC, 2012).

Floods have been linked to the dissemination of pathogens and hazardous chemicals over wider areas including agricultural areas, and also to increased likelihood of contact of humans and livestock animals with contaminated water. For example, Marcheggiani et al. (2010) found some apparent concurrence of main flooding events in several Northern Italian regions and the increased occurrence of infectious diarrhoea and disease linked to infection with Hepatitis A virus and *Legionella* (Marcheggiani et al., 2010).

In a more general sense, it is conceivable that flooding increases the likelihood that highly contagious pathogens that act via the oral-fecal route are spread through the environment and come into contact with human and animal recipients, either directly or indirectly. Indirect ways could include deposition on crops being consumed by man and animal (*e.g.,* pastures used for grazing, crop fields), or infection of food-producing animals with zoonotic pathogens that could form a risk for human consumers of animal-derived products. This may also be a consideration for agricultural lands that are purposefully used for flood management (*i.e.,* "river engineering"). With regard to chemical contaminants, for example, Albering, Van Leusen, Moonen, Hoogewerff, and Kleinjans (1999) found that, following a surge in river flow in the river Meuse in Western Europe in 1993–1994 (and subsequently in 1995), the flood deposits on river banks showed a higher content of heavy metals than in the underlying soil. Crops that were experimentally grown in these areas also showed uptake of heavy metals, such as cadmium, copper, lead, and zinc by leafy vegetables and copper by potatoes (Albering et al., 1999). An example of the spread of microbial pathogens by flooding is provided by Casteel, Sobsey, and Mueller (2006), who compared the pathogen loads of soils in Northern Carolina following the hurricane-related flooding of agricultural lands used for crop cultivation with those from pre-hurricane samples. It is known that hurricanes can cause severe weather, such as heavy precipitation and associated flooding, at distances far (*e.g.,* hundreds of miles) from the actual storm, such as had happened in the case studied by Casteel and colleagues. The authors thus observed that the levels of spores of *Clostridium perfringens*, which they considered a reliable indicator of fecal contamination, were increased by almost two orders of magnitude on average in post-hurricane-related-flooding samples as compared to pre-hurricane samples. The authors cautioned, though, that other contributing sources could not be completely discounted, yet concluded that the monitoring for indicator pathogens such as *C. perfringens* spores could support the risk management following flooding as a result of severe weather events (Casteel et al., 2006).

Various systems exist for flood prediction and monitoring, such as the Advanced Hydrological Prediction Service of the US National Oceanic and Atmospheric Administration's National Weather Service. This service offers a web-based feature which summarizes real-time measurements of hydrological data that are collected by automated data collection and processing systems operated by local, state, and federal agencies across the nation. The web interface shows, for example, a map on which, in a bird's eye view, the locations that are at risk of flooding can be identified [*i.e.*, highlighted in distinct colours (National Weather Service, 2012a)]. Moreover, to reduce the risks of flash floods in the Appalachian region of the US through improved flood warning capabilities, the National Weather Service, in collaboration with local, state, and federal agencies, has installed an automated warning system in twelve states in that area, which integrates the data from 1700 sensors (National Weather Service, 2012b). In Europe, the European Commission Joint Research Centre's Institute for Environment and Sustainability is setting up the European Flood Forecasting System. Scientists from this Centre have also assessed the predicted change in magnitude of extreme flood events in Europe caused by climate change. They compared the mean annual maximum discharge through rivers in two 30-year windows, *i.e.*, 1961–1990 versus 2071–2100, using the model used for predicting flooding in Europe combined with climate models. Based on the outcomes, the authors concluded that the maximum discharge in Northeastern Europe will decrease (leading to more drought) as caused by decreased snowfall and hence less snowmelt, while it is expected to show a more mixed pattern, including some regions showing significant increases, in other parts of Europe (Dankers and Feyen, 2009).

3.5. Heavy precipitation

According to the IPCC 2012 report, the frequency of heavy precipitation and the part that heavy rainfalls take in the total precipitation is likely to increase over many areas of the globe during this century, particularly at the high latitudes and in the tropical regions, as well as in the Northern mid-latitudes during winter. Also for some regions with an expected decrease in average precipitation (*e.g.*, Southern Africa, Western Asia, Western coast of South America), there is medium confidence that heavy precipitation events will increase (IPCC, 2012).

Various of the severe events described above are linked to heavy precipitation, such as the flooding of rivers and flash-flooding of non-river areas, and land- or mudslides caused by movement of land, mud, or sludge and failure of dams following episodes of heavy precipitation, as well as the role of alternating episodes of precipitation, heat, and drought on the growth of moulds on crops and the formation of mycotoxins by these moulds.

An additional hazard associated with heavy precipitation is the runoff of contaminants and microbial pathogens into surface water, subsequently contaminating, for example, food-producing water organisms or crops irrigated with these waters. Moreover, nutrients run off from lands (*e.g.*, phosphate from fertilized land) may stimulate the growth of harmful algal blooms (see Section 4 below). Boxall et al. (2009) provide a comprehensive review of the possible changes of transport to water bodies and other changes expected to occur under the influence of climate change that may alter food safety hazards. In one scenario, these authors note that, when the water-retaining capacity of the soil is saturated, the frequency of runoff events of particulates (*e.g.*, microbial pathogens) and sorptive contaminants (*e.g.*, hydrophobic compounds and heavy metals) through overland and macropore flow is likely to occur. Interestingly, these authors also establish a linkage with drought as soil drying during dry spells can make it more hydrophobic and also induce the formation of cracks leading to a better connected macropore system, both contributing to increased runoff during subsequent precipitation events (Boxall et al., 2009). For example, a model experiment carried out by Thurston-Enriquez, Gilley, and Eghball (2005) studied the bacterial and protozoan counts in the runoff from agricultural land fertilized with animal manure following artificial rainfall conditions, concluding that heavy precipitation events could thus significantly affect water bodies. Miller et al. (2005) observed that the odds for detection of *Cryptosporidium* spp. in haemolymph of mussels grown in different coastal areas of California (USA) with varying levels of freshwater influx and faecal contamination (*e.g.*, from livestock runoff) increased depending upon certain factors, such as the occurrence of a heavy precipitation event a week before sample collection (Miller et al., 2005).

An international initiative for global information on monitoring rainfall including heavy rainfall (*i.e.*, as a category of rainfall anomalies) worth mentioning is the Tropical Rainfall Measuring Mission (TRMM; as well as the upcoming Global Precipitation Measurement mission, GPM), jointly carried out by the US National Aeronautics and Space Agency (NASA) and the Japan Aerospace Exploration Agency (JAXA). This initiative utilizes satellite information from the TRMM satellite and other weather satellites employing radar, infrared, and microwave sensors and low inclination orbits in order to collect a range of data on global rainfall, clouds, and heat transfer for both research and event prediction. The user interface on the TRMM website features a number of world maps highlighting, for example, rainfall anomalies, tropical storms, and areas at risk of flooding (NASA, 2011).

3.6. Forest fires

Forest and other wildfires, while being a direct result of either human activity (*e.g.*, arson, lit cigarette butts, campfire, downed electricity lines) or lightning, can also be seen as an indirect consequence of a range of factors including climate-driven ones, such as a combination of drought with high ambient temperatures. In turn, such fires can also influence other hydro-meteorological events, for example by increasing the risk of landslides in affected areas (*e.g.*, forest-covered slopes) and that of certain types of convective storms (*e.g.*, pyro-tornadoes). The IPCC 2012 report reviews the literature on the occurrence of forest- and wildfires in relation to climate change and notes that an increasing trend has been observed. The example of the Melbourne Fire in Australia in 2009 is highlighted as an example where such fires occurred after an unusually extended period of drought combined with natural and human causes of incineration, with great impact on society (IPCC, 2012).

From the food safety point of view, forest fires are known as a potential source of airborne dioxins and other polyaromatic hydrocarbon (PAH) compounds, which are persistent organic pollutants formed by incomplete combustion that may contaminate food products through various environmental routes, for example by precipitation of dioxin-containing particles onto pastures (and subsequent uptake by grazing cattle, for example) or deposition into water bodies or land compartments, contributing to the background level of dioxin contamination that may bio-accumulate through the biological food chain. With regard to the possible linkage between forest fires (as opposed to landfill fires, waste incineration, etcetera, that have shown to contribute to food contamination) with food safety, scientific literature is scarce and not conclusive on this point. For example, a study on olives, which may be amenable to dioxin uptake based on the lipophilic properties of their cuticula and lipid content, showed the lack of an effect from forest fires on the content of dioxins, dioxin-like polychlorinated biphenyls (PCBs), and PAHs in olive oil from olives harvested at short distances from such fires in Greece, which occurred after a period of intense heat and dryness (Costopoulou et al., 2010).

3.7. Tropical storms

The impact of tropical storms on related weather events, such as heavy precipitation and flooding, is discussed for these particular events in the pertinent sections above. The IPCC (2012) report concludes that there is low confidence in an overall increase in tropical cyclone activity, while, for the future, it is considered likely that the frequency of tropical cyclones will decrease or stay essentially the same, and that the mean maximum wind speed will increase but not in all regions. It is also considered likely that the rates of rainfall related to tropical cyclone activity will increase with greenhouse gas warming. For the tracks of extra-tropical storms, it is considered likely that there has been a poleward shift (*i.e.,* towards the South and North Poles), while there is medium confidence that the average cyclone activity at mid-latitudes on both hemispheres will decrease (IPCC, 2012).

The hurricane season in the years 2004 and 2005 featured a number of the most destructive hurricanes in history, including the hurricane Katrina in 2005, which is estimated to have caused more than 81 billion US dollar damage in the United States of America (USA). Interestingly, the IPCC (2012) report notes that the heightened activity in 2005 does not represent a substantial departure from the variability in historic data (IPCC, 2012), indicating that this cannot be linked to the impact of climate change let alone human anthropogenic forcing. This notwithstanding, an interesting feature of the scientific research on the impact of Katrina is the comparison of the spread of chemical contaminants in the environment before and after Katrina, such as measured in the frame of certain environmental monitoring programmes. For example, Johnson, Kimbrough, Lauenstein, and Christensen (2009) measured organic and metal contaminants in oysters, which are water-filtrating organisms and therefore serve as sentinel for contaminants in the water environment, in the US coastal areas affected by hurricane Katrina. Given that oysters are also food organisms, this may also provide insight into the possible impacts of the hurricane on contamination of shellfish. The organic contaminants in their analysis included polyaromatic hydrocarbons (PAHs), and organochlorine compounds including residues of the pesticides chlordane, dieldrin, and dichlorodiphenyltrichloroethane (DDT), and polychlorinated biphenyls (PCBs). In general, the concentrations of organic contaminants were lower after Katrina than before it, except for high-molecular-weight PAHs, the latter reflecting possible spills of mineral oil as caused by the storm. By contrast, the oyster tissue levels of trace metals in general and in particular for lead and nickel tended to be higher after the hurricane than before. As an explanation for these phenomena, the authors postulate that the hurricane had led to increased levels of particulate matter in the water of rivers feeding into the coastal sea waters, which also lead to altered feeding behaviour of the oysters. Suspended particles may absorb organic contaminants, thereby decreasing their bioavailability for absorption by oysters and other molluscs. Moreover the increased salinity of inland waters by the storm surge may have caused desorption of trace metals from sediment and soils leading to increased availability of water-dissolved and particle-bound metals, both of which can be taken up by oysters, in the subsequent run-off. Notwithstanding these differences, the authors note that the contaminant levels still stayed below the FDA's action levels (Johnson et al. 2009). A number of other studies have focused on the levels of microbial pathogens and chemical contaminants in the floodwater, soil, and the sediment that precipitated from the floodwater within the city of New Orleans after the storm surge and breach of the levees protecting the city from an adjacent lake. While these studies focused on the potential risks associated with direct exposure of humans to these hazards, for example potential uptake through soil contact by children in playing fields, it is noteworthy that a number of pathogens (*e.g.*, *Vibrio, Aeromonas*) and contaminants (*e.g.*, lead and arsenic) that are also relevant to foods were found to be elevated in the environmental samples that were taken shortly after Katrina in comparison with pre-Katrina samples (Abel et al., 2010; Fox et al. 2009; Presley et al., 2006; Rotkin-Ellman et al. 2010). These outcomes also show the importance of monitoring to establish pre- and post-event values of pathogens and contaminants that may signal a potential concern for food and drinking water safety.

An example of a tropical storm monitoring system is the United States (US) National Oceanic and Atmospheric Administration's National Hurricane Centre. The centre's mission is to prevent loss of lives and economic damage, as well as to provide outreach based on its experience and understanding of the hazards caused by hazardous tropical weather. During the annual season between May and November, the centre's Hurricane Specialist Unit continuously provides public information, including updates at 6-h intervals and more frequently when threats are immanent, on storms when atmospheric depressions appear in the Northern Atlantic and Eastern Pacific Oceans. This is based on the monitoring, by a group of experts, of a range of meteorological data, including satellite images, data collected and transmitted by marine buoys, weather radar, and data collected by specially equipped aeroplanes. These data serve as the basis for predicting the track and intensity of storms using different predictive computer models as well as the experts' experience, the latter particularly when the models yield divergent track predictions. Besides the prediction of hurricanes, the centre's Tropical Analysis and Forecast Branch provides year-round marine weather information for ships, including forecasts and warnings of storms, sea waves, and precipitation. The centre also liaises with other national and international meteorological agencies, local and national media, and emergency managers in other local and federal institutions, who are thus provided with the necessary information to warn the public and take preventive and mitigating measures (National Hurricane Centre, 2012; Rappaport et al., 2009).

Such well-developed warning system and knowledge on food safety consequence of these storms enables risk managers in US to mitigate food safety risks at an early stage. It should be mentioned, however, that in many places in the world that are expected to encounter more of the weather extremes, food safety response and awareness may be less developed, especially for the indirect effects that may occur.

4. Proactive early warning of weather-driven food safety problems

Early warning systems for food safety can be divided into i) reactive systems which are endpoint- or hazard-focused and which are designed to monitor the food safety hazard or human-, animal- and plant diseases, ii) proactive predictive systems for known hazards such as systems developed for prediction of mycotoxin contamination of wheat and maize, and iii) “holistic” systems, which also take into account developments outside the food production chain that may eventually lead to the emergence of risks within this chain (Marvin, Kleter, Prandini, Dekkers, & Bolton, 2009). In particular, for the second category, systems have or are being developed that are, or may use, weather conditions to warn for a potential food safety problem. This section will describe the pros and the cons of some illustrative examples of this category of early warning systems for food safety. To the knowledge of the authors no systems are available of the third category, although their potential is being explored in Europe (EFSA, 2009b, pp. 1–34; Groeneveld, Willems, Broekstra, Van den Broek, & Top, 2009). In this section we also will describe what a 'holistic system" may look like.

4.1. Media monitoring and weather analysis

The occurrence of environmental disasters (*e.g.,* droughts, floods etc), disease outbreaks, and other events that are directly or indirectly related to food safety are often reported in the media and therefore these sources may be exploited as early warning for food safety risks. Various internet-scanning (news aggregation) software tools have been developed collecting reports related to infectious disease outbreaks and human health issues (Collier et al., 2008; Marvin et al., 2009). In Europe, the European Commission's Joint Research Centre (JRC) developed the European Media Monitor (EMM), which collects publications and reports from news portals world-wide that are available through the World Wide Web (WWW). EMM contains four portals, the NewsBrief, the News-Explorer, the Medical Information System (MedISys) and the EMM-Labs. NewsBrief collects all news items from around the world in 43 languages and categorizes these into hundreds of subject domains and allows the user to find news on specific subjects published in a country of interest. News directly related to food safety hazards (*e.g.,* pesticide contamination, melamine etc.) or indirectly (*e.g.,* floods, drought, disease outbreak etc.) are available via this portal. The MedISys portal is more specialized and presents articles and reports related to public health, categorized into hundred different categories (*e.g.,* diseases, symptoms, chemical agent, geographic regions, organizations etc) based on pre-defined keyword combinations (Linge et al., 2009) and warns the user with automatically generated alerts. Recently the European Food Safety Authority (EFSA) has explored this tool for its ability to function as an early warning system for food and feed hazards (EFSA, 2009a; Rortais, Belyaeva, Gemo, Van der Goot, & Linge, 2010). Although improvements are recommended, this study concluded that MedISys is suitable as an early warning system for food and feed hazards.

The World Health Organization (WHO) together with the Global Outbreak Alert and Response Network (GOARN) utilize the aggregator service Global Health Intelligence Network (GPHIN; Mawudeku and Blench, 2006), which monitors news feeds and web sites on a real time basis. It aggregates information on a broad range of topics from disease outbreaks to natural disasters. GPHIN is managed by Canada's Centre for Emergency Preparedness and Response (CEPR). This system was successful in providing alerts during the SARS epidemic, leading the WHO to claim that "GPHIN provided some of the earliest alerts to the November outbreak in China" (WHO, 2003).

The internet-based reporting system ProMED-mail is another system that report information on outbreaks of infectious diseases and acute exposures to toxins around the world that affect human, animal and plant health. Reports provided by this system may include warnings of potential effects of expected weather conditions on the spread of the disease and the potential food safety hazard. A typical example is shown in Fig. 1, showing a screenshot of ProMED on 13 July 2010. An outbreak of the sugarbeet disease *Cercospora* in weed beet near Luton, UK was reported and it was warned that the warm weather could cause the disease to spread rapidly. Furthermore, the farmers were considering the application of fungicides to address the disease.

4.2. Proactive predicting systems

4.2.1. Systems for mycotoxins

Worldwide several initiative are on-going for the prediction of mycotoxins, most of which are focused on small grain cereals and maize. These modelling initiatives have different characteristics and application potential. In some cases, the toxin is not predicted directly, but via the related plant disease (Rossi, Giosuè, Pattori, Spanna, & Del Vecchio, 2003; Van der Fels-Klerx and Booij, 2010). Also, models for predicting fungal plant disease are available. Although fungal disease models are undoubtedly helpful in crop disease management, their value for mycotoxin management is limited since the relationship between fungal plant disease and mycotoxins is variable. Therefore, for the aim of mycotoxin management of the crop, these hazards can better be predicted directly, rather than via disease manifestation (Van der Fels-Klerx and Booij, 2010).

The majority of the mycotoxin predictive models are empirical and model equations are based on data collected in the field, whereas only a few models are mechanistic (Van der Fels-Klerx and Booij, 2010). Most of the predictive models for mycotoxins are developed to be used by farmers with the aim of improving their decision making processes regarding the application of fungicides during crop growth. Hence, these farmer models focus on the critical growth period of the crop, *e.g.,* the flowering period of wheat. However, these models can also be used by other stakeholders, including feed and food industry and food safety authorities. A few models have specifically been developed for the latter stakeholders, and consider a prolonged part of the entire growth period (Van der Fels-Klerx, Burgers, & Booij, 2010), hypothesing predictions are more accurate as the growth period progresses. Besides the mathematical models, qualitative prediction tools for fungal disease and/or related mycotoxins are available, all aiming at farmer assistance (Forrer, Musa, Hecker, & Vogelgsang, 2006; Froment, Gautier, Nussbaumer, & Griffiths, 2011; Musa, Hecker, Vogelgsang, & Forrer, 2007).

One of the most well-known predictive models for mycotoxins in grain is DONcast, developed in Canada (Hooker, Schaafsma, & Tamburic-Ilincic, 2002). This model provides estimates of the mycotoxin deoxynivalenol (DON) in wheat at harvest. The predictions are made around wheat flowering, based on a combination of agronomical and weather-related factors (Schaafsma and Hooker, 2007). The DON forecasts are provided on a regional basis, linked to the weather station that is closest to the farm location. DONcast is commercially deployed in Canada. It is used by farmers to underpin decision making with regard to the use of fungicides. The model has also been adapted for use in Uruguay, South America (Hooker and Schaafsma, 2004) and is currently being validated in France (Schaafsma and Hooker, 2007).

In The Netherlands, a comparable approach was chosen to establish specific models to predict DON in winter wheat for two different groups of stakeholders. The models vary in the growth period considered, and the influencing factors (Van der Fels-Klerx et al., 2010). Also, a descriptive model for DON concentrations in wheat in North-West Europe has been constructed, for use in climate change impact assessment (Van der Fels-Klerx, Goedhart, et al., 2012, Van der Fels-Klerx, Olesen, Madsen, & Goedhart, 2012). In the Czech Republic, a neural network model has been developed for the prediction of DON in wheat (Klem, Vanova, Hajslova, & Sehnalova, 2007). Just like DONcast, model development in the latter two countries was based on country-specific field data, and final models include weather and agronomical variables.

For Italy, Rossi et al. (2003) developed a dynamic simulation model to estimate the risk of Fusarium Head Blight (FHB) and mycotoxin accumulation in wheat. The model calculates a daily

Fig. 1. Screenshot of ProMED-mail made on 13 July 2010.

infection risk for the four main species causing the disease, *i.e.*, *Gibberella zeae, Fusarium culmorum*, *Gibberella avenacea*, *Monographella nivalis*, which is accumulated over the growing season for each of the four fungi. For both *G. zeae* and *F. culmorum*, such a daily and total risk is also calculated for the production of the two mycotoxins DON and zearalenole.

Given their nature, empirical models cannot be applied to other conditions than the ones they are calibrated for. Before applications to other areas, they need to be calibrated for the local conditions. In theory, mechanistic models are more generic, but - just like the empirical models - their local application also needs being tested.

4.2.2. *Algal blooms warning systems*

Early warning systems for harmful algal blooms (HAB) can be separated into tools for the prediction of HAB occurrence and the species involved; real time observation systems, and the combination of the two.

Worldwide, different approaches and systems are in use to monitor HAB in coastal waters. They include toxin and cell detection – and their quantification – in water, aerosols, and (shell)fish. These monitoring activities are challenges due to the complexity and diversity of HAB, including multiple toxins, multiple toxic algal species, multiple toxic fisheries resources, and smaller and larger HAB events occurring intermittently. However, new technologies to address these challenges related to sampling and analysis are emerging. These new technologies include water sampling platforms, toxin measurement methods (including chemical, *in vitro*, and *in vivo* assays), and cell detection techniques; of which an overview is provided by Anderson (2008).

The actual locating of a surface HAB can also be accomplished via ocean colour remote sensing. Although the use of remote-sensing satellite images can improve the understanding on the spatial distribution of water, it is limited by clouds and spatial resolution. Also, the system is species-specific, which requires cell counts for species validation.

Modelling is a rapidly developing tool towards the prediction of many HAB species and occurrences. Heisler et al. (2008) distinguish two types of HAB predictive models that are useful for management applications: models that predict the general likelihood of occurrence of HAB species and models that predict explicit HAB occurrence in time and space (Heisler et al., 2008). The former are useful for the management of long-term actions to reduce the likelihood of future HAB occurrences, whereas the latter are useful at the local community level.

Various types of models are useful for predicting the general likelihood of HAB occurrence, ranging from simple (empirical) regression models that may yield correlation – without necessarily a biological foundation for cause and effect relationships (*e.g.*, Wong, Lee, & Hodgkiss, 2007) – and conceptual models that are useful in communicating general patterns (*e.g.*, Smayda and Reynolds, 2003). The development of explicit model predictions in time and space needs mechanistic models that describe the physical, chemical and biological interactions. As compared to empirical models, such models need more refinement to understand the physics, biology and chemistry of the environment. The ultimate goal of these models is to use real-life data obtained from instruments in an observatory system, assimilate these data and contextual meteorological and oceanographic observations into the models, and provide continually updated forecasts of bloom behaviour (Anderson 2008). Spatially explicit models linked to hydrodynamic models are gaining some success, such as the one for *Karenia brevis* in the Gulf of Mexico (Walsh et al., 2006) and *Alexandrium* blooms in the Gulf of Maine (McGillicuddy, Anderson, Solow, & Townsend, 2005).

For some species, general likelihood predictions are available for use in long term management regarding nutrients. Additionally, several types of real time monitoring systems collecting data on species and environmental conditions, linked with conceptual, statistical or mechanistic models are available to assist in predicting and detecting HAB in time and space (*e.g.,* Lee, Hodgkiss, Wong, & Lam, 2005; McGillicuddy et al., 2005; Stumpf et al., 2009). As an example, the forecast system for the Gulf of Mexico includes current bloom locations, future bloom locations, and areas of impacts for blooms of *K. brevis* (which produces brevetoxin). The systems uses a combination of satellite derived image products, wind predictions, and heuristic and numerical models (Stumpf et al., 2009).

In The Netherlands, the Generic Ecological Model has been developed, which includes physical, chemical and ecological processes to predict the algal composition (four species: diatoms, flagellates, dinoflagellates, and *Phaeocystis*) in the North Sea (Blauw et al., 2006; Los, Villars, & Van der Tol, 2008). The North Sea area is also covered by the NORWECOM model, which also combines physical, chemical, and biological model systems (Skogen, Svendsen, Jarle Berntsen, Aksnes, & Ulvestad, 1995). Both models have recently been used for assessing the impacts of climate change effects on harmful algal blooms in the North Sea (Friocourt, Skogen, Stolte, & Albretsen, 2012).

4.3. "Holistic" systems

Several publications have emerged (Kleter, Prandini, Filippi, & Marvin, 2009; Marvin et al., 2009; Periapt, 2008) that describe potential systems for identifying emerging risks. Besides information from reactive early warning systems and other sources within the food-production chain ("from farm to fork"), these systems also take into consideration hazards that originate from – or that are influenced by – events and developments that take place within sectors outside this chain. Such systems are often referred to as "holistic systems". If designed appropriately, "holistic" systems should be able to identify the development of a food safety problem at an early stage in its development, allowing pro-active measures to be introduced to prevent the problem. In Europe, such an approach is being explored and implemented by the European Food Safety Authority (EFSA, 2009b, pp. 1–34, 2010a, 2010b). For instance, it is anticipated by EFSA that trade volumes of selected food and feed commodities may provide useful data, as an additional indicator, for the identification of emerging food safety risks.

4.3.1. Identifying risks related to climate change

Climate change will be an important driver for food safety risks in the future. Once the relationships between climate-related changes and food safety risks in the food production chain have been established, data on climate-related changes can then be used to allow an early warning of these risks. Several reviews have been published (Boxall et al., 2009; Miraglia et al., 2009; Tirado et al., 2010) predicting that the projected climate-related changes in water- and land temperatures, drought and precipitation, and extreme weather events will affect the occurrence of a variety of food safety hazards including food-borne pathogens (*e.g., E. coli* O157, *Campylobacter*, *Salmonella*, *Listeria*, *Clostridium*, etc.), natural toxins (*e.g.,* mycotoxins, phycotoxins, and phytotoxins), agricultural chemicals (*e.g.*, pesticides), contaminants (*e.g.*, heavy metals, volatile organic and inorganic contaminants), and veterinary medicines (*e.g.,* antiparasitic substances and antibiotics). This information can be used to build a systematic "holistic" framework, which links weather trends (either extremes or slow changes) with food safety problems. The framework can utilize various existing early warning systems in order to obtain information on various elements, such as predicted weather patterns, crop and animal diseases/pests, and chemical and microbiological food safety hazards. Establishing the framework can also help identify existing knowledge gaps.

An example of this approach is shown in Fig. 2 and involves the use of a stepwise approach that includes i) the formulation of "indicators" that are related to a climate factor (*e.g.,* land and sea temperature, precipitation, weather extremes), ii) identification of food safety hazards that are linked to these indicators, and data sources, iii) quality assessment of the data sources and iv) subsequent monitoring. An indicator is defined as a measurement or an observation that provides information on the nature of an agent or process involved and the source of the risk (EFSA, 2007). In addition, food safety hazards can be identified that are related to the identified indicator. For monitoring each of the three related elements including i) climate factor, ii) indicator and iii) hazard, data sources (*e.g.,* monitoring and/or survey programmes, websites, databases, etc) have to be identified that can provide information on changes occurring at a given time and location. Data sources suitable for this purpose can include official monitoring and survey programmes of i) climate factors, ii) food safety hazards, and iii) plant-, animal- and human diseases. In addition, since environmental disasters (*e.g.,* droughts, floods etc), disease outbreaks, and other events that are directly or indirectly related to food safety are often reported in general news media, these media sources may be exploited as data sources. Various internet-scanning (news aggregation) software tools have been developed for collecting reports related to infectious disease outbreaks and human health issues (Collier et al., 2008; Marvin, Kleter, Prandini, et al., 2009) and results of these searches are published and freely available (see for example European Media Monitoring [EMM (EMM, 2012)], Global Health Monitor, Biocaster (Biocaster, 2012) and ProMED mail (ProMED, 2012). One concern when using data from these media sources is the reliability of the data compared to data originating from official monitoring and survey programmes. The reliability may need to be evaluated on a case-by-case basis. It is anticipated that a combined utilization of data sources of the three elements of the framework will enable the identification of the development of a food safety problem in an early stage, before it emerges. Since the number of data sources to monitor may be large, it is preferable to establish methods and procedures for (automatically) collecting, handling and (ideally) interpreting signals coming from these data sources, *i.e.,* changes in measured indicators that are considered sufficiently large for closer scrutiny. Automatic interpretation of these signals will probably require the use of a decision support system (Arnott and Pervan, 2005) that should be able to interpret the data from the relevant sources, and infer new information (alerts) from the interpreted data. Such a system, ideally avoids the generation of "false positive" and "false negative" alerts, in order to enable risk managers to set priorities for the mitigation and prevention of emerging risks.

In a sense these holistic approaches are a further enhancement to the existing early-warning systems that aggregate and assess information from different data sources. The enhancement needed to create a holistic system is two-fold: i) For a truly holistic approach multiple domains, not necessarily close to the food-safety domain (such as policy, geography, and economy) also need to be

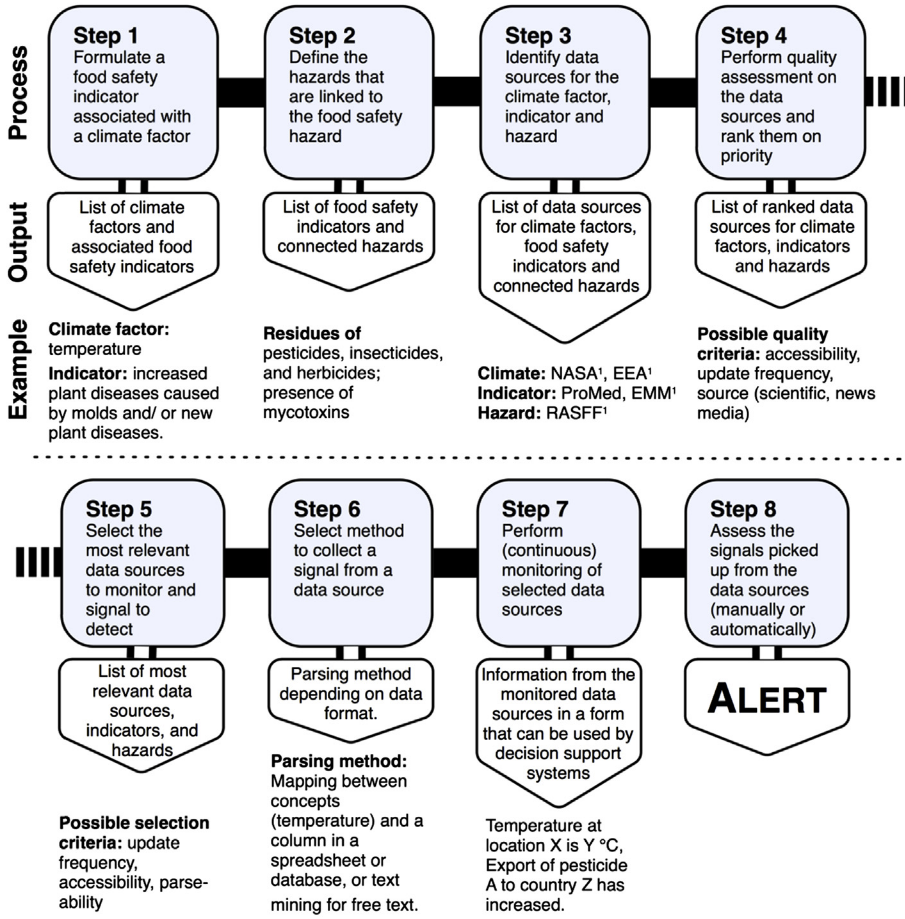

Fig. 2. An example of an early warning system for food and feed based on the "holistic approach" making use of climate factors. [1] :Explanation of abbreviation in the figure: NASA, National Aeronautics and Space Administration (http://climate.nasa.gov/); EEA, European Environment Agency (http://www.eea.europa.eu/); EMM, Europe Media Monitor (http://emm.newsbrief.eu/overview.html), RASFF, Rapid Alert System for Food and Feed (https://webgate.ec.europa.eu/rasff-window/portal/).

included. This includes the identification of suitable data sources. ii) It needs to be able to interpret and reason with the data accumulated via aggregation. Where reactive systems "only" need to monitor and assess existing information before presenting the data to a food-safety expert, holistic systems need to combine information from different data sources (Groeneveld et al., 2009) and this entails the interpretation of the data specific to a certain domain and the translation of the data as expressed using concepts from that specific domain into data expressed using concepts from the domain the evaluating food-safety expert is comfortable with. For instance, while the acronym DON may refer to mycotoxin deoxynivalenol in microbiology, it may also refer to the drug 2,5-dimethoxy-4-nitro-amphetamine in pharmacology, to the disease dysbaric osteonecrosis in medicine, or to the Department of the Navy as part of the U.S. Department of Defence. To correctly interpret information from different domains it is vital to precisely define the concepts that are used in each domain. When the information is expressed in terms of this 'super'-domain, decision support systems (Arnott and Pervan, 2005) can use the information to infer new data that may be pertinent for food-safety assessment where each small piece of data (from different domains) that led to the inference may not have been deemed important. For instance, climatic data that show that average temperatures in a certain region are increasing only become important for food-safety when combined with information from other domains that point to an increase in bovine diseases when temperatures increase and increase in the use of antibiotics when disease pressure increases. A decision-support system may infer that the farmers will increase the use of antibiotics for cattle.

Information-aggregations systems such as EMM often use lists of words or strings that are used during searching for information and when assessing information. These words represent certain concepts pertinent to that domain, where different words may represent the same concept ('DON' and 'vomitoxin'), but where one word ('DON') may also represent two different concepts ('deoxynivalenol' and '2,5-dimethoxy-4-nitro-amphetamine'). For a holistic system it is necessary to be able to not only find the correct words (strings) used to describe the information but to link it to the correct concept, so that it is clear that the information is about DON, the toxin and not DON as the Department of the Navy (Groeneveld et al., 2009). Furthermore, it is important for a decision support system that the list of concepts is hierarchically organised. We need to know that if we find the concept 'salmon' that the information is about a type of fish. This means that we need to make a connection between a concept ('fish') and its subconcepts ('salmon', 'herring', 'cod',...) although other types of relations may also prove usefull, for instance the occurrence of 'deoxynivalenol' (DON) is associated with the fungus *Fusarium graminearum*, where 'is associated with' is a new type of relation. Such lists of organised concepts are called ontologies (Davies, Grobelnik, & Mladenic, 2009).

Apart from the concepts (with a unique identifier) themselves, ontologies are therefore also built up from statements (or triples, or facts) of the form subject-predicate-object. For instance, the statement 'deoxynivalenol (DON) is associated with the fungus Fusarium graminearum' is made up of a subject ('deoxynivalenol (DON)'), a predicate ('is associated with'), and an object ('Fusarium graminearum'). While concepts such as 'deoxynivalenol (DON)' only give us the information that something exists, statements give meaning to these concepts. From the statement 'deoxynivalenol (DON) is a toxin', we can deduce that DON is a kind of toxin and if we also have the statement 'toxins may be hazardous when ingested as food', we may even deduce the fact that we should not ingest DON.

This deduction comes natural to us humans because we associate the word toxin with certain properties, one of which is that it should not be ingested, and when we identify DON as a toxin, we automatically assign the same properties to DON. To enable computer systems to make these kind of deductions we need to provide the system with some kind of reasoning ability. One approach that is often used is the use of an inference engine which uses inference rules to construct new facts from available data (Russel and Norvig, 2009).

Inference rules often come in the form of 'IF A and B or C THEN Y and Z'. Examples of such rules would be: 'IF X is a B and B constitutes a hazard when ingested THEN X constitutes a hazard when ingested'. If we set the value of X to 'deoxynivalenol (DON)' and the value of B to 'toxin' and we have the statements 'deoxynivalenol (DON) is a toxin' and 'toxin constitutes a hazard when ingested', then we can apply the inference rule because the condition of the rule ('IF X is a B and B constitutes a hazard when ingested') is satisfied. An inference engine will then add a new statement to the database stating that 'deoxynivalenol (DON) constitutes a hazard when ingested'.

A prototype of such a holistic system, the Emerging Risk Detection Support System (ERDSS; Groeneveld et al., 2009) was developed for the Dutch food authority (NVWA). This system uses a forward-chaining inference engine (Groeneveld et al., 2009; Russel and Norvig, 2009), which means that it tries to satisfy the conditions of the inference rules and if the conditions of a rule are satisfied the result of the inference rule are added as new statements to the database. The addition of new statements, either because they have been deduced using inference rules, or because a new statement has been found in new information gathered during the aggregation process on the internet, can result in the conditions of other inference rules being satisfied. In this way the addition of one statement (fact) found in a news feed can cause a cascade of inference rules being fired and the addition of many new statements. Some of these statements may be relevant to food safety even though the news feed in which the fact was found that caused the cascade was not related to food safety.

A possible enhancement to the ERDSS system would be the inclusion of a backward-chaining inference engine (Russel and Norvig, 2009) next to the forward-chaining engine employed in the prototype. In a backward-chaining engine the system tries to prove hypotheses by finding rules by which the hypothesis will be satisfied. The hypothesis would then be the result of an inference rule. It then tries to determine whether the conditions are satisfied.

The challenges for such a holistic approach include the creation of suitable ontologies for each domain that may be relevant, the creation of correct inference rules, and ways to extract information (as formalised statements using ontologies) from the different information sources and indicators. In the case of textual information, formalised statements can be extracted from the text by using Natural Language Processing (NLP). For integration of numerical data and models, a mapping between the measured/predicted values and the ontology needs to be created. It also involves the establishment of suitable thresholds for the measured/predicted data.

These activities can be automated but the resulting output should be evaluated by a team of experts from a variety of research disciplines before relaying the information to policy makers and/or risk managers (Groeneveld et al., 2009).

In conclusion, there is a wealth of data and information available on the World Wide Web (WWW) and elsewhere but this knowledge is scattered across many different locations and has been generated for many different purposes. The proposed "holistic" approach utilizes this data in a comprehensive and systematic manner to identify emerging risks to food safety. The projected effects of climate change will impose certain food safety risks either directly or indirectly. We believe that by developing and applying "holistic" systems for identifying emerging food safety risks that account for changes in climate, land-use and socio-economics, society will be better placed to mitigate against food safety risks in the future.

5. Conclusions and recommendations

The changing climate will have a pronounced effect on the agricultural production systems as we know today albeit the effect will vary per region and will depend on the flexibility of the production chains to anticipate the changing conditions. The major problem is that the projected weather changes do not occur linearly but instead follow a whimsical pattern, such as in the form of sudden and severe hydro-meteorological events. Yet the trends are clear: land and see temperatures are increasing, weather extremes are becoming more frequent, and increasing are the numbers (and length) of periods of drought and torrent rains, etc. These weather changes will have an effect on all living organisms, being human, animals, and plants but also on microorganisms. In many cases, such effects have been investigated and documented, such as in the reports that are cited and discussed in this review.

Worldwide many early warning systems that monitor food safety hazards that can cause health risks to human and animals or that monitor diseases to human, animals and plants are in place. The latter systems may also warn for the presence of food safety hazards. Generally, these monitoring systems will focus on known hazards and diseases and, hence, will miss or pick up with delay the occurrence of new hazards and/or known hazard in new food products. However, as shown in this review, the effect of the changing weather on the (re)occurrence of food safety hazards can be predicted (*e.g.,* predictive models for mycotoxins) which allows adaptation of current monitoring systems to detect the hazard at an early stage. In particularly, systems that collect publications on the internet may proof useful to anticipate on potential food safety problems. By better use of the available information and development of further information exchange between stakeholders worldwide, such as aimed for by for example FAO EMPRES or FAO GIEWS, the preparedness of authorities and actors in the food production chain may be stimulated and the negative impact of climate change on food safety can be minimized.

It is important that risk assessors and risk managers all over the world are aware of the many potential consequences of climate-change-driven food safety risks and that systems are in place that warn of the development of food safety problems at an early stage of development. This is particularly relevant for regions less experienced and/or with less capacity to anticipate climate-change-driven food safety problems. Because of globalisation of food chains, food safety problems are not confined to specific areas but may move quickly around the world.

It is therefore recommended to undertake the following actions:

1. Better utilization of the information sources which are already available on the internet and to stimulate information exchange between stakeholders around the world.

2. The development of future scenarios of land use, social, technological and economic change in order to assess how inputs of chemicals and pathogens to the food chain may change in the future. Given the potential contribution of imported food as a source of disease burden and issues of traceability back to food processing, imported goods should also be considered.
3. The development of targeted surveillance schemes for presence of pathogens and chemical and biological contaminants in food.
4. Development of experimental datasets on impacts of different parameters that will change under climate change on different food safety pressures.
5. Development of new exposure models for contaminants in food products that account for changes in climatic and other variables.

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