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Climate change and food safety: A review

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ABSTRACT

Climate change and variability may have an impact on the occurrence of food safety hazards at various stages of the food chain, from primary production through to consumption. There are multiple pathways through which climate related factors may impact food safety including: changes in temperature and precipitation patterns, increased frequency and intensity of extreme weather events, ocean warming and acidification, and changes in contaminants' transport pathways among others. Climate change may also affect socio-economic aspects related to food systems such as agriculture, animal production, global trade, demographics and human behaviour which all influence food safety.

This paper reviews the potential impacts of predicted changes in climate on food contamination and food safety at various stages of the food chain and identifies adaptation strategies and research priorities to address food safety implications of climate change. The paper concludes that there is a need for intersectoral and international cooperation to better understand the changing food safety situation and in developing and implementing adaptation strategies to address emerging risks associated with climate change.

1. Introduction

There are many factors that affect food safety such as global trade, socio-economic and technological development, urbanization and agricultural land use. Climate change and variability are among the multiple factors that can provoke changes in the nature and occurrence of food safety hazards. These hazards can arise at various stages of the food chain, from primary production to consumption, and climate change may have direct and indirect impacts on their occurrence.

There are many pathways through which climate related factors may impact food safety including: changes in temperature and precipitation patterns, increased frequency and intensity of extreme weather events, ocean warming and acidification, and changes in the transport pathways of complex contaminants.

Temperature increases and changes in rainfall patterns have an impact on the persistence and patterns of occurrence of bacteria, viruses, parasites and fungi and the patterns of their corresponding foodborne diseases. Such changes also have an impact on microbial ecology and growth, plant and animal physiology and host susceptibility which may result in the emergence, redistribution and changes in the incidence and intensity of plant and animal diseases and pest infestations, all of which could impact foodborne diseases and zoonoses (FAO, 2008c). In this context climate change and variability also pose a challenge to pest and diseases control measures such as Good Agriculture and Good Veterinary Practices with potential implications for the presence of chemical residues in the food chain.

Extreme weather events such as floods and droughts may lead to contamination of soil, agricultural lands, water and food and animal feed with pathogens, chemicals and other hazardous substances, originating from sewage, agriculture and industrial settings. Emergency situations after natural disasters are of special concern for water and food sanitation.

Ocean warming, and climate change related acidification and changes in ocean salinity and precipitation also affect the biochemical properties of water, along with water microflora, fisheries distribution, fish metabolic rates, and persistence and patterns of

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occurrence of pathogenic vibrios, harmful algal blooms and chemical contaminants in fish and shellfish.

In addition to the relatively direct impacts of climate change on food contamination and foodborne diseases, climate change and variability may affect other underlying drivers of food safety such as agriculture, crop production and plant health, animal production and animal health, fisheries, aquaculture, food trade, food and feed manufacturing, processing and handling and consumer's behaviour. These impacts in turn have substantial public health, economic, social and environmental consequences. A better understanding of all the changes that might arise in view of climate change and variability is an essential first step to ensuring preparedness for emerging food risks.

2. Methods

This review consists in the secondary analysis of international literature on the effects of climatic factors on microbiological and chemical food contamination, foodborne diseases, animal and plant health, biotoxins and other food safety risks.

In preparation for the High-Level Conference on World Food Security: The Challenges of Climate Change and Bioenergy in 2008, the Food and Agriculture Organization of the United Nations (FAO) organized several expert consultations on the impacts of climate change on diverse issues related to food security, including the impacts on animal and plant health, implications for emergencies, etc. FAO also commissioned the production of background documents on the impacts of climate change on food and nutrition security, food safety and other relevant subjects. Among many sources of information, this paper reviews the background documentation on the impacts of climate change on food safety; the outcomes of the FAO expert consultations on climate change, trans-boundary diseases and pests; and the consultation on climate change and emergencies that were prepared for the FAO High-Level Conference on the Challenges of Climate Change in 2008.

The definitions of the terms related to food safety and the framework used to analyze the impacts of climate change on food safety correspond to the FAO description of a food control system (FAO/WHO, 2003). Definitions of the terms related to climate such as climate change and variability, vulnerability and adaptation correspond to those included in the Glossary of the Intergovernmental Panel for Climate Change (Baede, 2007).

3. Climate change and food safety impacts

The interactions between climate change and variability and food contamination, food safety and foodborne diseases are very complex since there are many associated uncertainties. This section reviews the impacts of climate change on food microbiological and chemical contamination and associated foodborne diseases, including the potential impacts of climate change on the formation and contamination with biotoxins such as marine toxins and mycotoxins.

3.1. Microbiological food contamination and associated foodborne diseases

Climate related changes may impact all three elements of the epidemiologic triad (host, agent, and environment). Climatic factors can affect (1) the sources and modes of transmission and (2) the growth and survival of pathogens in the environment and the microbial ecology and (3) the food matrix, among others (FAO, 2008c). Table 1 presents a summary of the microbiological agents that could be affected by climate change. The complexity of the ways of transmission illustrates the susceptibility of these environments to be affected by climatic factors, in particular extreme weather events involving flooding.

3.1.1. Climate factors and diarrhoeal syndromes

Diarrhoeal disease is one of the most important causes of ill–health in the world and is climate sensitive, showing strong seasonal variations (Kovats & Tirado, 2006).

Higher temperature has been found to be strongly associated with increased episodes of diarrhoeal disease in adults and children in Peru, where diarrhoeal reports increased 8% for each degree of temperature increase (Checkley et al., 2000). Associations between climate-related extreme weather events and monthly reports of outbreaks of infectious water-borne disease also have been reported worldwide (Confalonieri et al., 2007). Populations with poor sanitation infrastructure and high burdens of infectious disease often experience increased rates of diarrhoeal diseases such as cholera, cryptosporidiosis and typhoid fever after flood events. Increases in waterborne and foodborne diarrhoeal disease have been reported in India, Brazil, Bangladesh, Mozambique, and USA, following flooding episodes (Cairncross & Alvarinho, 2006) and have been predicted in Mexico (Hurtado-Díaz, Moreno-Banda, Riojas-Rodríguez, Sánchez-Meneses, & Castañeda-Martínez, 2009) and in Taiwan (Huang et al., 2009). A climate change scenario study investigating the burden of gastroenteritis associated with increasing temperature in Australia showed that the number of cases was predicted to rise substantially over the coming century (Bambrick, Dear, Woodruff, Hanigan, & McMichael, 2008).

Foodborne diarrhoeal diseases that have been identified as a priority for more routine monitoring because of changing climate conditions include salmonellosis, campylobacteriosis, vibriosis, listeriosis, other bacterial infections, parasitic infections, viral diarrhoeal syndromes (ECDC, 2007).

3.1.2. Bacterial contaminants and foodborne diseases

All foodborne pathogens and their associated diseases are potentially affected by climate change (ECDC, 2007). Time series analysis studies on the impacts of climate change on foodborne diseases have focused mostly on salmonellosis and campylobacteriosis in Europe, Canada and Australia.

3.1.2.1. Salmonellosis. A time series analysis study on human salmonellosis in several European countries showed that, in general, cases of salmonellosis increased by 5–10% for each one-degree increase in weekly temperature, for ambient temperatures above about 5 °C (Kovats et al., 2004). In Ireland increases of around 2% in the incidence of salmonellosis may be expected in coming decades as a result of climate change (Cullen, 2009). Similarly, a relationship between increasing temperature and salmonellosis reports has been reported in Canada and in Australia (Bi, Zhang, Hiller, & Cameron, 2009; D'Souza et al., 2004; Fleury, Charron, Holt, Allen, & Maarouf, 2006).

A climate change scenario study which predicted outcomes until 2100 in Australia estimated that the number of cases of gastroenteritis will rise over the coming century, due to increases in cases caused by Salmonella and other bacteria (Bambrick et al., 2008). Zhang, Bi, and Hiller (2009) predicted that, due to climate change alone and with all the factors remaining constant, there would be a doubling of the morbidity associated with salmonellosis in South Australia by the year 2050 directly. A potential 1 °C increase in weekly mean maximum temperatures may bring about 7% more *Salmonella* infections in cities such as Adelaide (Bi et al., 2009). The effect of temperature on *Salmonella* is quite consistent across a range of different countries and cities.

Infection with *Salmonella Enteritidis* appears to be more sensitive to the effects of environmental temperature, at least as compared with infections caused by *Salmonella Typhimurium* (Kovats

Table 1
Examples of microbiological agents that could be affected by climate change and variability and their mode of transmission to humans.

Bacteria	Host	Mode of transmission to humans
Salmonella	Poultry and pigs	Faecal/oral
Campylobacter	Poultry	Faecal/oral
Vibrio spp.	Shellfish, Fish	Faecal/oral
E. coli O157	Cattle and other ruminants	Faecal/oral
Anthrax Clostridium	Livestock and wild birds	Ingestion of spores through environmental routes, water, soil and feeds. Associated with outbreaks of after droughts
Yersinia	Birds and rodents with regional differences in the species of animal infected. Pigs are a major reservoir	Handling pigs at slaughter is a risk to humans
Listeria monocytogenes	Livestock	In the northern hemisphere, listeriosis has a distinct seasonal occurrence in livestock probably associated with Feeding of silage
Leptospira	All farm animal species	Leptospirae shed in urine to contaminate pasture, drinking water and feed
Virus	Host	Mode of transmission to humans
Rift Valley fever Virus	Multiple species of livestock and wildlife	Blood or organs of infected animals (handling of animal Tissue), unpasteurized or uncooked milk of infected animals, mosquito, hematophagous flies
Nipah virus	Bats and pigs	Directly from bats to humans through food in the consumption of date palm sap (Luby & et al., 2006). Infected pigs present a serious risk to farmers and abattoir workers
Hendra virus	Bats, and horse	Secretions from infected horses
Hantavirus	Rodents	Aerosol route from rodents. Outbreaks from activities Such as clearing rodent infested areas and hunting.
Hepatitis E virus	Wild and domestic animals	Faecal-oral. pig manure is a possible source through contamination of irrigation water and shellfish
Encephalitis tick borne virus	Sheep, goats	Unpasteurized milk
Parasites	Host	Mode of transmission to humans
Tapeworm *Cysticercus bovis*	Cattle	Faecal-oral
Liver fluke	Sheep, cattle	Eggs are excreted in faeces
Protozoan parasites		
Toxoplasma Gondii	Cats, pigs, sheep	Cat faeces are a major source of infection. Handling and consuming raw meat from infected sheep and pigs
Cyptosporidium	Cattle, sheep	Faecal-oral transmission. Waterborne. (Oo)cysts are highly infectious and with high loadings, livestock faeces pose a risk to animal handlers
Giardia	Cattle, cats, dogs	Faecal-oral transmission. Waterborne

et al., 2004). There appears to be a relationship between increases of human salmonellosis and elevated temperature during the week preceding the onset of the disease, suggesting, that inappropriate storage temperature and food handling may be important factors in the transmission (Kovats et al., 2004). This is in accordance with modeling results of the WHO/FAO microbiological risk assessment for *S. Enteritidis* in eggs (FAO/WHO, 2002).

3.1.2.2. Campylobacteriosis. The Climate Change and adaptation strategies for human health time series analysis study investigated the impacts of weather and climate change on campylobacteriosis in 15 countries from Europe, Canada, Australia and New Zealand (Kovats et al., 2005). Most countries in Europe show an early spring peak (April or May) in *Campylobacter* infection, however, not all countries follow this pattern. In Canada, the peak occurs in late June–early July. The seasonality is less pronounced in Australian cities as compared to New Zealand (Kovats et al., 2005). Within countries, there can be geographical variation in the seasonal patterns.

The role of climate related parameters such as short-term increases in temperature on human campylobacteriosis is unclear (Kovats et al., 2005). Despite the apparent relationship between temperature and campylobacteriosis, time series studies have shown this effect is confined to temperatures between about 5 and 10–15 °C, corresponding to the spring months (Tam, Rodrigues, O'Brien & Hajat, 2006). Skelly and Weinstein (2003) also reported that the association between elevated ambient temperature and increased likehood of *Campylobacter* transmission is as best weak, in contrast to the strong association observed between ambient temperature and *Salmonella* transmission. However, a recent Irish study predicted a 3% increase in the incidence of campylobacteriosis in coming decades as a result of climate change (Cullen, 2009). There are various potential transmission routes of campylobacteriosis (water supplies, bird activity, fly activity and recreational contact) that could also be affected by weather. Clearly, additional work is needed to characterize the impact of climate on the transmission of *Campylobacter* to humans (Kovats et al., 2005; Kovats & Tirado, 2006).

3.1.2.3. Vibriosis. Higher temperatures, sea level elevation, heavy precipitation, flooding and changes in water salinity may all have an impact on water microflora including aquatic human pathogens such as the pathogenic *Vibrio* spp. (FAO, 2008c). Ocean warming and changes in salinity have been shown to have an impact on aquatic microorganisms such as *Vibrio vulnificus* and *Vibrio parahaemolyticus*, important human pathogens typically transmitted by the consumption of molluscan shellfish harvested from warm-southern estuarine waters in the US Gulf Coast of Mexico (Drake, DePaola, & Jaykus, 2007; Paz, Bisharat, Paz, Kidar, & Cohen, 2007; Zimmerman et al., 2007). During the last 15 years there has been a significant shift from sporadic cases of *V. parahaemolyticus* towards large outbreaks attributed to the consumption of oysters harvested from northern waters linked to higher mean water temperatures (Drake et al., 2007; McLaughlin et al., 2005). Also over the last decade, a unique serovar (O3:K6) of *V. parahaemolyticus* has emerged and spread and rapidly throughout the world becoming pandemic in scope (Fuenzalida et al., 2007; Matsumoto et al., 2000). Such rapid changes in the epidemiology of *V. parahaemolyticus* infection are notable, even though a definitive relationship to global climate change has yet to be made. The global epidemiology of *V. vulnificus* infection has also changed. For example, while usually sporadic in nature, a 1996 outbreak of wound infection and bacteraemia occurring in Israel and associated with a unique isolate is notable. This *V. vulnificus* biotype appears to be a particularly virulent hybrid which was actually present in brackish waters for years to decades before causing disease in 1996. Paz et al. (2007) hypothesized that changes in water temperatures of inland fish farms promoted the growth of the organism, leading to an increased risk of infection in humans handling or consuming fish grown in these waters. Subsequent time series analysis of air temperatures for the two decades spanning 1980–1999 revealed a statistically significant increase in summer temperatures, which peaked at the same time that the organism began to be associated with human disease. Again, while not definitive, this evidence suggests a role for global climate change in emergence of this strain.

Vibrio cholerae is perhaps the best model for understanding the potential for climate-induced changes in the transmission of an enteric pathogen. Although low levels of the organism can be isolated from estuarine waters worldwide, the disease is endemic in only certain regions of the world (mainly the tropics and subtropics). In these areas, there are characteristic epidemic peaks (which are frequently seasonal) followed by periods of relative quiescence. The factors driving cholera endemicity are believed to be due to a complex interplay of environmental and biological factors (Lipp, Hau, & Colwell, 2002). Abiotic (environmental) factors, including temperature (most important), salinity, iron concentration, and sunlight, influence *V. cholera* toxin production and also phytoplankton and zooplankton populations. This complex set of interactions together impact survival and proliferation of *V. cholerae* in the estuarine environment. Although a simplistic summary, it should be apparent that even moderate changes in these critical environmental factors, which could easily occur due to climate change, can have important ramifications on cholera transmission, yet again with the developing world bearing the brunt of the public health impact. This is supported by a recent study which demonstrated that seasonal variation in the number of cholera patients in Bangladesh could be partly explained by temperature and rainfall (Hashizume, Wagatsuma, Faruque, Taiichi Hayashi, & Armstrong, 2009). More specifically, the first and second peaks of infection appeared to be attributable to low and high rainfall, respectively, while low temperature explained the winter trough.

3.1.2.4. Other bacterial foodborne diseases (FBD). Other bacterial agents of foodborne disease may also be impacted by global climate change. The fact that many, if not most foodborne bacterial pathogens can grow at room temperature with faster growth favoured at elevated temperatures means that increases in ambient temperatures may also speed up the rate of pathogen proliferation along the production to consumption continuum, all other factors remaining unchanged (FAO, 2008c). Cases of gastroenteritis caused by enteric pathogens such as *Clostridium*, *Vibrio*, *Aeromonas* spp. appear to peak in summer or have a positive relationship with ambient temperature (Bambrick et al., 2008). However, more recent work in the UK calls into question the impact of temperature and climate change in increased incidence of these foodborne diseases in England and Wales (Lake et al., 2009).

3.1.3. Viral foodborne diseases

Viruses do not grow in foods and many of the viruses which cause gastroenteritis in human do not have a readily demonstrated relationship to ambient temperature (Bambrick et al., 2008). However, human noroviruses are the most commonly identified cause of both sporadic cases and outbreaks of viral infectious diarrhoea in developed countries, have a winter time seasonality. Specifically increases in norovirus infection have been associated with cold, dry temperature, low population immunity and the emergence of novel genetic variants in Europe (Lopman, Armstrong, Atchison, & Gray, 2009).

Three major routes of viral contamination of foods have been identified: human sewage and faeces; infected food handlers; and animals for zoonotic viruses (FAO/WHO, 2008). Hence the most commonly implicated foods are fresh fruits and vegetables, raw molluscan shellfish and ready-to-eat foods contaminated by food handlers. All these routes may be influenced by climate-induced changes. For example flooding can result in the overflow of untreated human sewage, resulting in increased likelihood of enteric virus contamination during the production of fresh produce and molluscan shellfish. In addition, it appears that the survival and transferability of many human enteric viruses depends upon environmental parameters such as temperature and relative humidity (FAO/WHO, 2008).

3.1.4. Parasitical agents and foodborne diseases

There is causal relationship between climate change and emerging parasitic diseases (Poulin & Mouritsen, 2006). Temperature and other climatic variables have direct and indirect effects of on parasite transmission and this makes difficult to predict how climate change may impact on any given parasites or their hosts.

3.1.4.1. Protozoan parasites. Several studies in different geographical regions US and Europe show that climate related variability, such as intense rainfall and changes in precipitation affect the incidence of parasitical foodborne and water-borne diseases transmitted by protozoan parasites such as cryptosporidiosis and giardiasis (Confalonieri et al., 2007; ECDC, 2007; Curriero, Patz, Rose, & Lele, 2001). While these diseases are generally waterborne they can be also transmitted by contaminated foods such as raw vegetables (Tirado & Schmidt, 2001).

3.1.4.2. Foodborne trematodes. Global warming and increased temperature may affect the transmission cycle of trematodes (Poulin & Mouritsen, 2006). Important zoonotic foodborne trematode infections affect to more than 40 million people per year worldwide and more than 50% global burden of foodborne trematodes is in SE Asia and W Pacific (WHO/FAO, 2002). Foodborne trematodes are transmitted by the consumption of raw or undercooked freshwater fish, crabs, crayfish and plants and may affect aquaculture products. About 70 species of foodborne trematodes are known to infect humans. Foodborne trematodes of public health significance in Asia include trematodes from the genus: *Fasciola*, *Fasciolopsis*, *Clonorchis*, *Opisthorchis Paragonimus*, *Haplorchis* and *Metagonimus*. Despite the serious human health consequences of these foodborne trematode infections (they can affect the liver, biliary system, pancreatic duct, the pleural cavity and lungs; and occasionally the brain) these are neglected diseases that affect some of the poorest populations in the world.

All trematodes use molluscs (generally snails) as first intermediate hosts. The production of cercariae in snails is a fundamental component of the parasite's overall transmission which is directly influenced by temperature: within the range of temperatures in which host and parasite can live, an increase in temperature is almost invariably coupled with an increase in cercarial output. Small increases in air and water temperature forecast by many climate models will not only influence the geographical distribution of trematodes, but may also promote the proliferation of their infective stages in many ecosystems (Poulin & Mouritsen, 2006).

3.1.5. Vector-borne diseases and foodborne transmission

Climate change is a critical factor in the transmission of vector-borne diseases worldwide (Confalonieri et al., 2007). Some important vector-borne diseases have been found to be transmitted by foods.

3.1.5.1. Alimentary tick-borne encephalitis. Several Eastern European countries have reported outbreaks with alimentary Tick-borne encephalitis attributed to unpasteurized goats' milk (EFSA, 2006). Tick-borne encephalitis virus had been identified as a one of the top climate change-mediated vector-borne human disease in Europe (ECDC, 2007). Information on its prevalence in milk producing animals is limited and needs to be monitored.

3.1.5.2. Chagas' disease. American trypanosomiasis (Chagas disease) is caused by an intracellular parasite *Trypanosoma cruzi* which is transmitted by triatomine bugs and its distribution is limited to the Americas. Foodborne transmission of trypanosomiasis in the Americas have been reported since the mid 20th century (Pereira et al., 2010). If indoor temperatures rise, vector species in the domestic environment may develop shorter lifecycles and higher population densities (Carcavallo & Curto de Casas, 1996). High temperatures also accelerate development of the pathogen, *T. cruzi*, in the vector (Asin & Catala, 1995). The outbreak of foodborne transmitted trypanosomiasis reported in Brazil in 2005 was associated with ingestion of sugar cane juice that was found to be contaminated with crushed *Triatoma infestans*, the vector of trypanosomiasis in Brazil (Pereira et al., 2010). Outbreaks of foodborne transmitted trypanosomiasis have been associated with contaminated juice in Brazil, Venezuela and Colombia (Pereira et al., 2010). The phenomenon of foodborne transmission of trypanosomiasis should be further investigated particularly in view of the challenges of climate change and variability.

3.2. Other zoonoses, animal health and veterinary public health issues affected by climatic factors

Climate change is one of the multiple factors driving the emergence and spread of animal diseases and the transfer of zoonotic pathogens from animals to humans. Other factors refer to ecosystem diversity, function and resilience, others being changes in the structure of the livestock industry, in breeding and husbandry practices and in international trade in livestock and animal products (FAO, 2008b). These factors are not independent from each other and climate change interacts with each of them.

3.2.1. Climate change and emerging zoonosis

The risk of emerging zoonosis may increase due to climate related changes in the survival of pathogens in the environment, changes in migration pathways, carriers and vectors and changes in the natural ecosystems.

Zoonosis such as Rift Valley fever, West Nile Fever, tick-borne diseases and non-zoonotic animal diseases such as Blue tongue, African Horse Sickness, African swine fever are examples of animal diseases whose distribution will be strongly influenced by climate change and variability (Easterling et al., 2007; EC, 2009).

3.2.2. Climate change impacts on animal health and veterinary public health: potential pathways

Pathways through which climate change may impact animal health and veterinary public health issues include:

- Increase in the susceptibility of animals to disease.
- Increase in the range or abundance of vectors/animal reservoirs and prolonging the transmission cycles of vectors.
- Impact of climate change on farming/husbandry practices (including the use of veterinary drugs).

3.2.2.1. Increase in animal susceptibility to disease. Climate may have a direct or indirect influence on the susceptibility of animals to disease. Climate change affects animals' living conditions which are conducive to pathologies such as parasitic diseases (e.g. infestation/affection by nematodes and taenia), nutritional disorders, sunstroke or dehydration (EC, 2009). Exposure to intense cold, droughts, excessive humidity or heat may predispose cattle to complex bacterial syndromes such as mastitis which may require the use of antibiotics.

Aquatic animals particularly vulnerable to climate change because their related metabolic processes are influenced by water temperature, salinity, and oxygen levels and their ecosystems are fragile. Fish, including shellfish, respond directly to climate fluctuations as well as to changes in their biological environment (predators, species interactions, disease). In the aquaculture sector, problems expected from a warming environment include a greater susceptibility of disease, particularly in intensive systems (Shriner & Street, 2007).

3.2.2.2. Increase in the range or abundance of vectors/animal reservoirs and prolonging the transmission cycles of vectors. Because of the sensitivities of the vectors and animal hosts of these diseases to climactic factors, climate change-driven ecological changes, such as variations in rainfall and temperature, could significantly alter the range, seasonality, and incidence of many zoonotic and vector-borne diseases (CDC, 2008). Climate change will be especially important to vector-borne and rodent-borne diseases and macroparasites of animals and may also result in new transmission modalities and changes in host species (FAO, 2008a; FAO, 2008b).

Vector-borne pathogens which respond most rapidly to climatic changes are likely to be rapidly evolving promiscuous agents, transmitted by rapidly reproducing, highly mobile and habitat-generalist vectors. Temperate countries will be particularly vulnerable to invasions by exotic vector-borne virus diseases (FAO, 2008b).

3.2.2.3. Impact of climate change on farming/husbandry practices. The impact of and responses to rising temperatures for farming practice are likely to differ across the world. Livestock breeds less susceptible to heat may be used, but this change may increase susceptibility to certain pathogens. In some areas, more animals may be moved inside in an attempt to avoid heat exposure and stress, giving increased opportunity for transmission of disease. Conversely, increased temperatures will increase the length of the grass-growing season in some areas, which could allow more extensive livestock grazing and greater exposure to vectors and wildlife, FAO (2008c).

Changes in animal husbandry practices (e.g. intermingling or crowding of food animals) in response to natural disaster or climate-induced changes might promote the transmission of pathogens between animals, resulting in greater pathogen load in faeces and increased prevalence of carcass contamination.

The proliferation of animal diseases due to climate related changes may result in an increased use of veterinary drugs that could lead to increased and possibly unacceptable levels of veterinary drugs in foods of animal origin (FAO, 2008a). This may have public health and trade consequences.

3.3. Toxinogenic fungi and mycotoxin contamination

Climate change can affect infection of crops by toxigenic fungi, the growth of these fungi and the production of mycotoxins. Mycotoxins are naturally occurring substances produced by toxigenic fungi that commonly grow on a number of crops and that cause adverse health outcomes when consumed by humans and animals. Mycotoxins have plagued mankind since the beginning of organised crop production (FAO, 2001) and probably before. Once studied as a problem arising during the storage of commodities, it is now clear that almost all, if not all of mycotoxin problems originate in the standing crop as a result of the interaction between the crop plant, the mycotoxin-producing fungus and bio-physical factors.

3.3.1. Mycotoxins and food safety

Direct human dietary exposure to mycotoxins occurs through consumption of contaminated crops. Mycotoxins can also reach the human food supply indirectly through animal products (e.g. milk) from livestock that have consumed contaminated feed. At high doses mycotoxins produce acute symptoms and deaths but, arguably, lower doses that produce no clinical symptoms are more significant to public health due to the greater extent of this level of exposure. Particular mycotoxins may possess carcinogenic, cytotoxic, immunosuppressive, neurotoxic, estrogenic or teratogenic activity, some more than one of these (Smith & Moss, 1985). Characteristically, the various mycotoxins attack specific target organs so are associated with characteristic pathological patterns which can, along with sensitivity, vary between animal species (Smith & Moss, 1985).

Exposure of human populations to mycotoxins is not purely due to occurrence of mycotoxins in the food chain since the amount and type and quality of commodity consumed varies and choices can be made. Appreciating how these choices are made is important if we are to be in a position to predict and control human exposure in a time when we expect to see significant changes in our food supply systems from global climate and environmental change. Fig. 1 elaborates these relationships.

Since there is a relation between food availability and mycotoxin intake, periods of poor harvests should receive special attention from the authorities. In view of climate change, some crops may become inappropriate to a region but re-organising food production systems accordingly may prove difficult because of public preferences. Variation in seasonal performance of crop plants could increase as existing weather patterns break down and new ones form raising the prospect of serious intermittent threats to food security and public health.

One approach to preventing exposure is to impose limits on mycotoxin content in commodities. In industrialized countries there is often legislation of acceptable limits and testing with monitoring programmes to enforce these limits but there is a lack of uniformity and, indeed, capacity internationally (Anon, 2004; Van Egmond, 1995). In the context of international trade, such regulations would protect a population from exposure to highly contaminated lots but does not remove the toxins from the international food chain. Some argue that limits encourage surreptitious adulteration of clean lots with contaminated material toward the limit.

Due to the public health and economic implications the most commonly legislated mycotoxins are the aflatoxins, ochratoxin A, deoxynivalenol, fumonisin, zearalenone and patulin. It should be noted that measuring the extent of contamination is not a trivial exercise and there is no firm relation between mycotoxin content and other measures of commodity quality.

Economic implications of mycotoxin contamination include trade disruptions – this food safety hazard accounted for the highest number of notifications in 2006 within the EU Rapid Alert System for Food and Feed (EC, 2007). It also negatively affects productivity in the livestock and crop sectors.

3.3.2. Environmental and climatic influence on mould and mycotoxin contamination

From Fig. 1, the occurrence of mycotoxins (frequency by concentration) results from the interaction of fungi with crop plants. The performance of each 'partner' is mutually affected by the condition of the other as they respond to the prevailing physical conditions of weather and soil. Indirect effects of climate change are expressed through the other biological components of the system, referred to as the unit community comprising pests, most obviously, and the array of commensal organisms inhabiting the phylloplane, soil or interior spaces of the plant.

Producing predictive models is a good means of producing testable hypotheses and focusing studies to improve our understanding of these interrelations. Considerable effort has been committed to predictive models of plant pathogens (Garrett, Dendy, Frank, Rouse, & Travers, 2006), however many of these fungi are obligate or near-obligate pathogens of the host, very different to the natural history of mycotoxigenic fungi. There are models designed to predict seasonal mycotoxin contamination that rely on local short-term weather parameters linked to precise plant lifecycles, detail that would be impossible to extract from climate change models but these may provide a useful starting point (Schaafsma & Hooker, 2007).

A particular environmental change will not influence all species of mycotoxigenic fungi in the same way. There are physical conditions under which a particular fungus will compete better so, for example, increasing average temperatures could lead to changes in the range of latitudes at which this fungus is able to compete. These fungi have one or more host plants with which they are

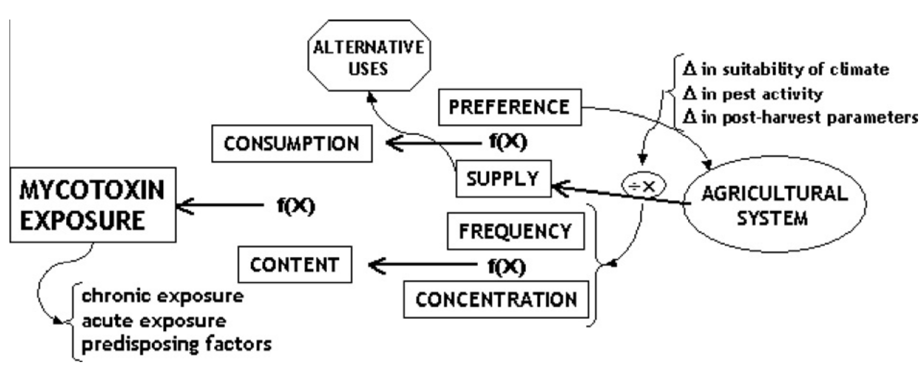

Fig. 1. Framework describing exposure to mycotoxins. Reading from left to right, the level of mycotoxin exposure will accrue via a function of consumption levels and mycotoxin content and is significant in light of acute and chronic exposure levels accounting for any predisposing factors. The consumption profile develops as a function of supply of food and preference, a parameter influenced by ability to acquire the preferred food. The mycotoxin content is characterized as a function of frequency of occurrence and concentration of mycotoxins in these contaminated lots. The agricultural system endeavours to supply sufficient amounts of the foods in demand but the suitability of 'normal practice' to accomplish this, including post-harvest routines, depends on the climate and when the climate deviates outside of normal bounds, both mycotoxin levels and food supply will be affected through physical factors as well as biological ones such as pest activity. '$f(x)$' represents some mode of interaction producing an outcome. 'Δ' = change.

associated so will be constrained by the range and performance of the host (see following sections). In addition, temperature, humidity and precipitation and the temporal pattern of these parameters are known to have an effect on how toxigenic moulds interact with their plant hosts in producing mycotoxins and the broader biological communities of our agricultural ecosystems.

Experiments with enhanced CO_2 levels, usually a doubling from 350 ppm to 700 ppm has shown that photosynthetic rates of C-4 plants are only marginally increased while those of C-3 plants are increased by more than 25%. Nitrogen content of the foliage is reduced and other compositional parameters change so it is likely that new interactions and new patterns of interaction will emerge over time (USDA, 2008).

Conditions adverse to the plant (drought stress, temperature stress, stress induced by pest attack, poor nutrient status, etc.) encourages the fungal partner to develop more than under conditions favourable to the plant with the expectation of greater production of mycotoxins. Whereas moist, humid conditions should favour mould development, this can be mitigated by the vigour of the host if these conditions suit it. Changes in the geographical range of crops produced could provide opportunity for new fungus plant associations to arise and perhaps mycotoxins currently not considered as a threat to public health such as sterigmatocystin, cyclopiazonic acid, moniliformin or neurotoxins produced by *Penicillium* species might require re-evaluation.

3.3.3. Climate change, mould growth and mycotoxin contamination

The most widespread and studied mycotoxins are metabolites produced by species of the genera *Aspergillus*, *Penicillium* and *Fusarium* (CAST, 2003). This section reviews the likely impacts of climate related factors on the occurrence of mycotoxins from these three important mould genera.

3.3.4. Fusarium toxins

Species of the genus *Fusarium* are responsible for the occurrence of several major toxins in commodities including trichothecenes (e.g. Deoxynivalenol and T 2-toxin), fumonisins, fusarin C, moniliformin and zearalenone (Miller, 2008). The most important species in this connection are *Fusarium verticillioides*, *F. proliferatum* (section Liseola); *F. sporotrichioides*, *F. poae* (section Sporotrichiella); *F. graminearum*, *F. culmorum*, *F. crookwellense* (section Discolor). These fungi are probably best thought of as very close associates of plants with important stages of their natural history conducted in soil.

Maize is grown from tropical to temperate regions and throughout its range *F. verticillioides* is usually present as an endophyte. In addition, members of the Discolor group are found and *F. graminearum*, considered to be the more virulent plant pathogen, tends to predominate in the warmer temperate regions (periods of daytime temperatures of 25–28 °C) with *F. culmorum* more common in the cooler temperate regions. In wheat, barley and rye the Discolor group species predominate noting these grains' range is limited to cooler regions than is maize. Strains of *F. graminearum* produce either deoxynivalenol (DON) or nivalenol (NIV) and zearalenone (ZER) while *F. culmorum* produces only DON and ZER (Miller, 2008).

There are reports that a series of warm European summers has seen the occurrence of the formerly predominant species, *F. culmorum*, fall to be replaced by *F. graminearum* (Miller, 2008). European strains of *F. graminearum* commonly produce NIV so further warming due to climate change would be expected to favour *F. graminearum*, the species that is the more virulent plant pathogen and perhaps a shift to a NIV/ZER contamination pattern from DON/ZER pattern in Europe and Asia. In the Americas this would not occur since most American *F. graminearum* strains are DON producers. At temperatures above about 28 °C however Liseola species are strongly favoured.

Liseola group species do not produce trichothecenes or ZER but they do produce fumonisins (FM) and moniliformin (MON). Though *F. verticillioides* can be considered ubiquitous in maize (*F. proliferatum* is also common), FM and MON are not and one reason for this lies in the interaction of maize and this endophyte of maize. It is reported that FM occurrence is correlated to drought stress and indeed, dry season maize as in southern and east Africa can contain large amounts of this toxin in maize of very good appearance while Fm in significant amounts in north temperate zones is much less common. Because *F. verticillioides* is favoured at higher temperatures one could anticipate that a warming trend would see the region where this fungus can dominate the other maize-borne *Fusarium* species shifting to higher latitudes. At the same time, higher temperatures would cause higher evapo-transpiration rates so that even if there were to be no reduction in rainfall, drought stress would be more common and therefore so should FM and perhaps MON. If the scenario of less reliable or shifting annual rainfall patterns is also realised, it could intensify this effect.

F. verticillioides is also common in rice, where it is an important pathogen responsible for bakane (foolish rice disease, the symptoms are caused by gibberellic acid production by the mould) and a sheath rot, and though FM has been detected in rice and isolates from rice are as capable of FM and MON production as isolates from maize, these compounds are currently not common in this commodity (Desjardins, Plattner, & Nelson, 1997).

3.3.5. Aspergillus and Penicillium toxins

These important toxigenic fungi occupy an ambiguous ecological position. It is certain that many, perhaps most of the species of these genera are primarily soil fungi but the most important species, from the point of view of mycotoxin contamination, appear to be genuine associates of plants. Of the host of toxic compounds collectively produced by this group, the three most important are the aflatoxins (AF), ochratoxin A (OTA) and patulin. Aflatoxin produced by *Aspergillus flavus*, *A. parasiticus*, *A. nomius* and *A. wentii*, is a genotoxic carcinogen, is also a potent acute toxin, and is widely distributed but associated especially with maize, groundnuts, tree nuts, figs, dates and certain oil seeds such as cottonseed. Aflatoxin contamination of susceptible crops in some hot dry regions of the American South-West has made it economically infeasible to grow these crops in the region (Robbens & Cardwell, 2003).

The producing fungi are widely distributed from the tropics through the low latitude temperate zone but can occur almost anywhere in food systems. There does not appear to be a single mode of infection of the host plant but high toxin levels tend to be correlated with some sort of damage or stress of the host. In Maize, attack of the cob by various caterpillars, head blight (caused by *Fusarium* spp.) and drought are all reported to stimulate AF accumulation. In groundnut, infection takes place during flowering but, usually, strong development of the fungus and appreciable AF contamination is seen after drought conditions during crop development. In pistachio it may be that mechanical damage caused by premature splitting of the hull and navel orange worm attack are important contributory factors leading to late infection of the seed but it is clear there is infection of un-split fruit (Sommer, Buchanan, & Fortlage, 1986; Thomson & Mehdy, 1978). In cottonseed, a high background contamination is exacerbated by wet weather after bole opening (Cotty & Jaime-Garcia, 2007). It has been suggested that a general warming trend will both increase insect pest numbers and their range (USDA, 2008) so where mycotoxin contamination is enhanced by insect pest activity one would predict a correlation between warming and contamination.

The impact of climate change on plants adapted to a semi-arid climate, like pistachio, is unclear. There are reports that periods of higher than average temperatures and reduced annual rainfall have already been experienced in Kerman Province in Iran and increased rates of nut deformity and increased levels of aflatoxin contamination has been recorded (Ministry of Jihad-e-Agriculture I.R. of Iran, 2008).

Other species of *Aspergillus* and *Penicillium* genera are also producers of two other important mycotoxins – OTA and Patulin – specific discussion of these is not included here. Plant stress does not seem to be an important factor in these cases. Patulin is only significant in pomaceous fruit and juices and ciders made from them, a fact that reflects the close association of the producing fungus, *Penicillium expansum*, to apples and pears (Moake, Padilla-Zakour, & Worobo, 2005). OTA is associated with various seed crops, including some nuts, and grapes and, consequently, in beverages such as wine, beer and coffee.

3.3.6. Other drivers of fungal colonization and mycotoxin production affected by climate change

Factors influenced by climate such as insect and other pest attack, soil condition and nutrient status and agro-industrial methodology are potential and indirect triggers of fungal colonization and mycotoxin production.

3.3.7. Insects and other pests

Pest and disease agents can favour colonization by toxigenic fungi and mycotoxin contamination in several crops. The response of insects and plant diseases to the foreseen climate change is poorly understood and Petzoldt and Seaman (2005) conclude that the precise impact of climate change on insects and pathogens is somewhat uncertain. However, most evidence indicates that there will be an overall increase in the number of outbreaks of a wider variety of insect pests.

Fungal distribution and cycle are largely influenced by insect attack in a number of ways including the lowered resistance of plants to stress and the mechanical damage (wounds) on kernels or fruit that favour infection by the fungus. The influence of these factors depends on the characteristic of the insect, the plant and the fungus. Notably, there are reported examples of the ability of insects to protect plants from fungal attack (Dowd, 1992a; Dowd, 1992b).

3.3.8. Post-harvest conditions

It is common for commodities to contain mycotoxigenic fungi at harvest with or without significant levels of mycotoxins. Up to the point of harvest, the status of the plant will play a major role in determining the degree of mycotoxin contamination while the condition of the grain to be stored is a major factor in its stability during storage. If climate change alters the nature or degree of variation of conditions in the harvest/post-harvest period so stability of the crop between harvesting and marketing of the commodity will 'in some cases' be adversely affected. One can anticipate that adjustments in post-harvest handling techniques and practice will be required.

In the simplest terms post-harvest handling will consist of some kind of cleaning, which may be conducted concomitantly with harvest, drying then storage where stability is maintained by restricting water availability uniformly throughout the stack to a level well below that required for fungal growth. For the most part these problems have technological solutions but in regions where capital investment on such production infrastructure is lacking any emerging problems will be most clearly manifest.

Historically, acute mycotoxicoses have been diseases of the poor especially during shortages of food. Whether global climate change will affect food supply in terms of quality and quantity to the extent that it will be felt by the relatively well off is an open question. Small-holders in the developing world, however, eat what they cannot sell and the best of their production is what can be sold. With poor city dwellers, food accounts for the greatest proportion of their income so they buy what they can afford. These groups are the most vulnerable to the effects of mycotoxins in the diet now and in the future.

3.4. Harmful algal blooms and fishery product safety

During recent decades, there has been an apparent increase in the occurrence of harmful algal blooms (HABs) in many marine and coastal regions (Fig. 2, Hallegraeff, 1993). Quantitatively estimating the extent of this apparent increase in HAB events is difficult due to the fact that the increase in HAB occurrences may be a result of increased awareness and better monitoring (Glibert, Anderson, Gentien, Granéli, & Sellner, 2005; Hallegraeff, 1993). Fig. 3.

3.4.1. Harmful algal blooms and fishery products safety

Toxin-producing HAB species are particularly dangerous to humans. A number of human illnesses are caused by ingesting seafood (primarily shellfish) contaminated with natural toxins produced by HAB organisms; these include amnesic shellfish poisoning (ASP), diarrheic shellfish poisoning (DSP), neurotoxic shellfish poisoning (NSP), azaspiracid shellfish poisoning (AZP), paralytic shellfish poisoning (PSP), and ciguatera fish poisoning and cyanobacteria poisoning. These toxins may cause respiratory and digestive problems, memory loss, seizures, lesions and skin irritation, or even fatalities in fish, birds, and mammals (including humans) (Anderson, Glibert, & Burkholder, 2002; Sellner, Doucette, & Kirkpatrick, 2003). Some of these toxins can be acutely lethal and are some of the most powerful natural substances known; additionally, no antidote exists to any HAB toxin (Glibert et al., 2005). Because these toxins are tasteless, odourless, and heat and acid stable, normal screening and food preparation procedures will not prevent intoxication if the fish or shellfish is contaminated (Baden, Fleming, & Bean, 1995; Fleming et al., 2006). To the date very few epidemiological studies on the human health impacts of HABs have been carried out (Moore et al., 2008).

In addition to human health effects, HABs also have detrimental economic impacts due to closure of commercial fisheries, public health costs and other related environmental and socio-cultural impacts (Hallegraeff, 2010; NOAA – CSCOR, 2008; Trainer & Suddleson, 2005).

3.4.2. Impact of temperature change on persistence and patterns of occurrence of algal communities

Changes in climate may be creating a marine environment particularly suited to HAB-forming species of algae. Two major functional groups of marine algae, or phytoplankton, cause toxic HABs – diatoms and dinoflagellates. The majority of HAB-forming phytoplankton species are dinoflagellates, with approximately 10–12 taxa primarily responsible for the current expansion and regional spreading of HABs in the sea (Smayda, 1997). Dinoflagellate abundances have increased to the detriment of diatom populations in some marine ecosystems, such as the North-East Atlantic (Edwards, Johns, Leterme, Svendsen, & Richardson, 2006), the Grand Banks area of the North-West Atlantic (Johns, Edwards, Richardson, & Spicer, 2003) and Baltic Sea (Wasmund & Uhlig, 2003). This shift in community composition has been linked to increased sea surface temperature (SST); in the North-East Atlantic, increased SST during winter months has resulted in an earlier growth and succession of flagellates (Edwards & Richardson, 2004; Edwards et al., 2006). Additionally, dinoflagellates are well-suited to stratified water (Margalef, 1978) and therefore may not only respond physiologically to temperature, but may also respond indirectly if climate warming enhances stratified conditions or if stratification occurs earlier in the season (Edwards & Richardson, 2004).

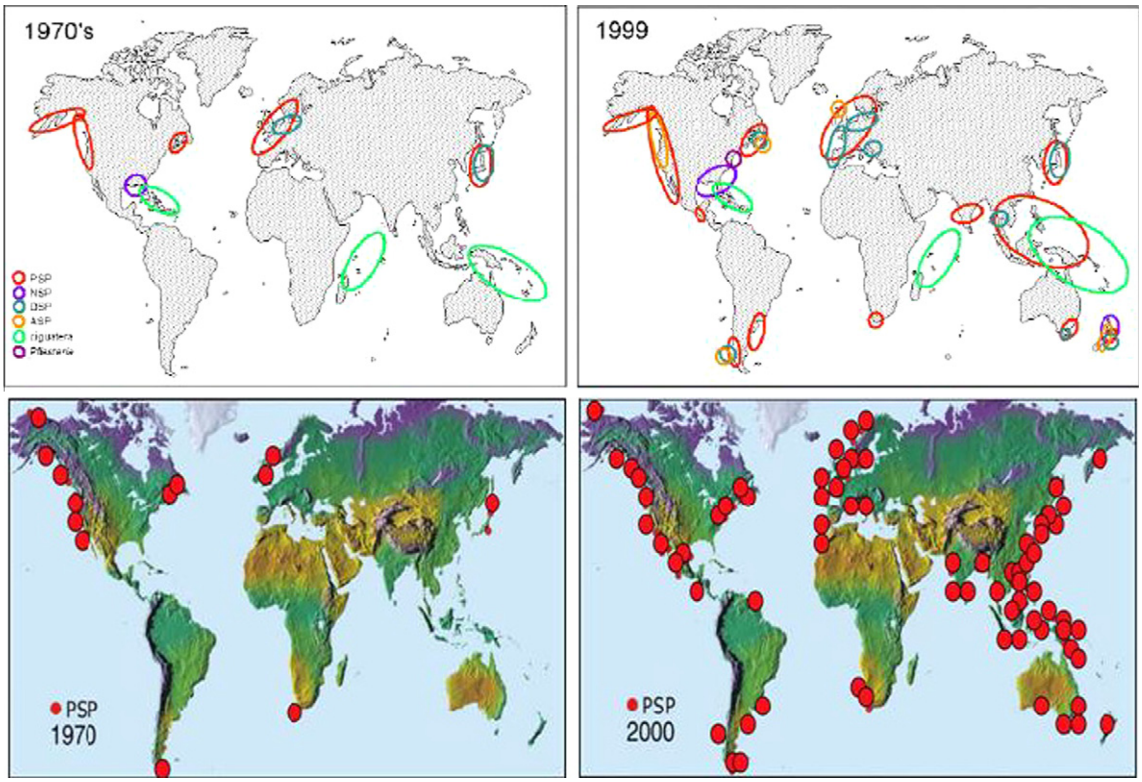

Fig. 2. Global distribution of HAB toxins and toxicities (reproduced from Dolah (2000) and detail of increase in PSP outbreaks (from Glibert et al. (2005)).

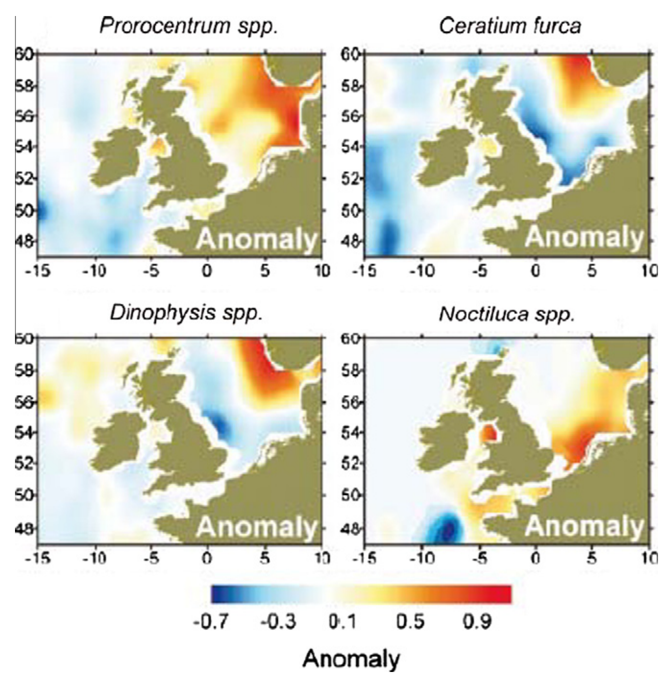

Fig. 3. Anomaly maps signifying the difference between the long-term mean (1960–1989) and post-1990s distributions of some key dinoflagellate species in the North-East Atlantic. Shades of red signify values above the long-term mean and shades of blue signify values below the long-term mean. Reproduced from Edwards, Johns, Licandro, John, and Stevens (2007). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Experimental results suggest warming SST and increased water stratification may lead to an increase in growth rates of some HAB taxa including *Prorocentrum* spp. and *Dinophysis* spp. (Peperzak, 2003). Increasing SST has also been found to lead to decreased surface nutrient concentrations which favour the smaller dinoflagellates and are detrimental to the larger diatoms (Bopp, Aumont, Cadule, Alvain, & Gehlen, 2005). Thus, it appears that in some areas regional climatic changes favour dinoflagellates over diatoms, therefore increasing the likelihood of occurrence of HAB-forming species. However, the extent to which regional climate change will influence HAB dynamics is uncertain as separating the effects of climate change from natural variability remains a key scientific challenge.

As SST increases with regional climate change, the temporal period during which HABs occur annually may also expand. Recent work in Puget Sound suggests that by 2100 the period of optimal growth of the toxic dinoflagellate *Alexandrium catenella* may potentially expand from its historical length of 68 days to up to 259 days due to warmer water temperatures (Moore et al., 2008). This would have severe implications to regional food safety as shellfish farming is an important industry in Puget Sound and, as *A. catenella* produces paralytic shellfish toxins which may result in death if consumed by humans (Quayle, 1969), and blooms of this species necessitate the cessation of local shellfish harvesting.

The relationship between phytoplankton biomass and HAB species toxicity is complex. Toxic HABs can have harmful effects even if the species is not dominant and toxin production may be related to hydro-climatic conditions and can very among strains within a species, even during the course of one bloom event (Barin et al., 2005). Some species, such as *Alexandrium fundyense*, can cause significant toxicity in shellfish even when present at very low abundances (Barin et al., 2005) while others are only toxic at high concentrations (Anderson et al., 2002). Even some species of the same genus possess varying levels of toxicity (Trainer & Suddleson, 2005). Furthermore, if bacterial growth increases with climate change, the toxicity of some HAB species may also increase; however further work is needed to define the relationship between bacteria and algal toxin production (Richardson, 1997).

In addition to changes in community composition, increased SST has resulted in changes in geographical distribution of some phytoplankton groups and species. The spatial–temporal distribution of several HAB-forming dinoflagellates in the North-East Atlantic has recently been studied with respect to regional climate change (Edwards et al., 2006). Since 1990, areas of the North Sea and North-East Atlantic which have warmed the most have significantly increased in abundance of both toxic HAB-forming dinoflagellates such as *Prorocentrum* spp. and *Dinophysis* spp. as well as *Noctiluca* spp. and *Ceratium furca*, the decomposition of whose blooms result in oxygen depletion which may lead to benthic mortalities (Fig. 2, Edwards et al., 2006). A similar range expansion of *Noctiluca* spp. has been observed in Australian waters during the last 50 years (Hallegraeff, Hosja, Knuckey, & Wilkinson, 2008). Although *Noctiluca* is not toxic, this observed range expansion suggests that biogeographical shifts in the plankton are occurring in southern waters as well as northern, and suggests that toxic species could potentially undergo range expansions as well. Areas undergoing rapid warming may therefore be among the most vulnerable to increased HABs. Additionally, biogeographical boundary shifts in phytoplankton populations made possible by climate change also have the potential to lead to the poleward-spread of HAB species normally suited to milder waters (Edwards et al., 2006; Hallegraeff et al., 2008). This may result in an increased number of HAB species in some marine and coastal regions. For example, the range of *Gambierdiscus toxicus*, a toxic tropical dinoflagellate associated with ciguatera fish poisoning, is expected to extend to higher latitudes as its macroalgal habitat increases with the increased hurricane intensity and warmer SST (Moore et al., 2008). The recent discovery of the first recorded modern trans-Arctic migration of a plankton species due to reduced ice cover in the Arctic (Reid et al., 2007) further heightens the danger that a toxic subspecies may have the opportunity to colonize areas currently inhabited by only non-toxic forms of the same species.

Besides a general spread in their distributions, there is also evidence that HABs are becoming more frequent in some areas. In the eastern North Sea, for example, the frequency of occurrence of exceptional blooms has tripled since 1980 (Edwards et al., 2006). This increase is almost certainly related to changes in the hydro-climatic regime of the region, including hydro-climatic factors such as increased sea surface temperature, decreased salinity, variability in wind speed and changes in inflow from the North Atlantic to the North Sea. Additionally, some HAB-forming dinoflagellates form resting cysts during their lifecycles. Cysts sink to the sea floor and when environmental conditions are conducive to growth they break open to 're-seed' the area with the species. Some cysts can remain viable for tens of years, but if growth conditions occur more frequently, if for example one of the requirements is SST above a certain minimum temperature, cysts may be expected to reseed more often, causing HAB blooms (Dale, 2001).

3.4.3. Impact of sea level rise, increased precipitation and flash floods on harmful algal communities

In addition to changes in climate, increased anthropogenic nutrients are thought to be a key cause of HABs (Hallegraeff, in press; Sellner et al., 2003). Sea level rise, increased precipitation and flash floods are most likely to affect harmful algal communities through increased release of the nutrients nitrogen (N) and phosphorous (P) to coastal and marine waters. Increased concentrations of N and P without a corresponding increase in Si may cause changes in phytoplankton community composition, favouring dinoflagellates, which have no biological requirement for Si, at the expense of diatoms (Officer & Ryther, 1980; Smayda, 1990). Such a shift in the phytoplankton community towards dinoflagellate dominance may result in increased numbers of HAB species in regions prone to increased anthropogenic nutrients.

Measures taken in order to prevent or lessen the severity of impact of sea level rise and flash flooding may also alter nutrient loads to coastal waters. For example, the Iron Gates dam built on the Danube River was found to more efficiently retain Si than N or P. This, along with increased N and P loads, resulted in an increase in non-diatom blooms in the northwest Black Sea, including those of some HAB species, as well as an increase in bloom intensity (Humborg, Ittekkot, Cociasu, & Bodungen, 1997; Moncheva, Doncheva, & Kamburska, 2001).

3.5. Environmental contaminants and chemical residues in the food chain

There are many pathways through which global climate change and variability may impact environmental contamination and chemical hazards in foods. The section that follows synthesises existing evidence of chemical contamination of the environment associated with climate-related extreme events, ocean warming and changes in surface temperature and humidity that could result in food safety chemical hazards. The discussion below also highlights challenges for animal and plant health management and discusses possible implications for chemical residues in foods and in the environment.

3.5.1. Flooding and environmental contamination

Contamination of agricultural and pastureland soil with PCBs and dioxins have been associated with climate change related extreme events, particularly with the increased frequency of inland floods. Soil contamination can be attributed to remobilization of contaminated river sediments which are subsequently deposited on the flooded areas. In other cases, contamination of the river water bodies, and subsequently of the flooded soils, may have resulted from mobilization in upstream contaminated terrestrial areas such as industrial sites, landfills and sewage treatment plants.

Following the huge Elbe and Mulde floodings in Central Europe in 2002 a series of research and monitoring programmes were conducted in order to assess the contamination of the flooded and to identify transfer into the food chain. Results of the monitoring programmes showed very high levels of polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs) present in soil in periodically flooded pastureland riverside of the dikes, and grazing on the floodplains revealed a significant transfer of PCDD/Fs into milk (Umlauf et al., 2005). While the uptake of contaminated soils during grazing is an important factor considering the transfer into the food chain, barn feeding of properly harvested greens from the same floodplains is less critical (Umlauf et al., 2005).

Sources of chemical contamination of floodwater following Hurricane Katrina included oil spills from refineries and storage tanks, pesticides, metals and hazardous waste (Manuel, 2006). Several chemicals, such as hexavalent chromium, manganese, p-cresol, toluene, phenol, 2,4-D (an herbicide), nickel, aluminium, copper, vanadium, zinc, and benzidine were detected in flood water. Trace levels of some organic acids, phenols, trace cresols, metals, sulfur chemicals, and minerals associated with sea water were also detected (Environmental Protection Agency, 2005). Concentrations of most contaminants were within acceptable short-term levels, except for lead and volatile organic compounds in some areas (Pardue et al., 2005).

3.5.2. Contamination of waters

Higher water temperatures, increased precipitation intensity, and longer periods of low flows exacerbate many forms of water pollution, including sediments, nutrients, dissolved organic carbon, pathogens, pesticides and salts (Kundzewicz et al., 2007). In regions where intense rainfall is expected to increase, pollutants (pesticides, fertilisers, organic matter, heavy metals, etc.) will be increasingly washed from soils to water bodies (Boorman, 2003; Environment Canada, 2004). Higher runoff is expected to mobilize fertilisers and pesticides to water bodies in regions where their application time and low vegetation growth coincide with an increase in runoff (Soil, 2003).

Because of compaction, heavy rainfall after drought can result in more severe runoff and an increased risk of certain types of contamination. Alternating periods of floods and drought can therefore aggravate the problem.

3.5.2.1. Ocean warming. Increasing ocean temperatures may indirectly influence human exposure to environmental contaminants in some foods (e.g., fish and mammal fats). Ocean warming facilitates methylation of mercury and subsequent uptake of methyl mercury in fish and mammals has been found to increase by 3–5% for each 1 °C rise in water temperature (Booth & Zeller, 2005). Temperature increases in the North Atlantic are projected to increase rates of mercury methylation in fish and marine mammals, thus increasing human dietary exposure (Booth & Zeller, 2005).

3.5.2.2. Sea level rise. Sea level rise related to climate change is expected to lead to saltwater intrusion into aquifers/water tables in coastal areas. This will extend areas of salinisation of groundwater and estuaries, resulting in a decrease in freshwater availability for humans, agriculture and ecosystems in coastal areas. One-quarter of the global population lives in coastal regions; these are water-scarce-less than 10% of the global renewable water supply-(WHO, 2005a) and are undergoing rapid population growth. Millions of poor people in developing countries may experience limited use of water as a food ingredient due to underground water salinisation caused by climate related sea level rise.

3.5.3. Soil contamination

3.5.3.1. Alternating periods of droughts and floods. Agriculture soil and water contamination and variation on levels of contaminants have been associated with alternated periods of floods and droughts. The frequency of these seasonal periods will be increased due to climate variability and change.

Arsenic-rich groundwater is widely used for irrigation in Bangladesh during the dry season leading to increased levels of arsenic (As) in soils. Monsoon flooding leads to a reduction of topsoil-As contents almost to levels existing before irrigation. However, there are indications that As concentrations in soil are increasing over-time because of irrigation with As-contaminated water. Data are, however, insufficient in terms of quantity and quality and it is thus still unclear under what specific conditions and over what period of time As is accumulating in the soil. There is a risk of As contamination in soils affecting crop production. Concentrations of this contaminant in rice are increasing over-time because of the prolonged input of contaminated irrigation water (Dittmar et al., 2007; Heikens, 2006; Islam et al., 2005).

3.5.3.2. Environmental degradation and accelerated desertification. Impacts of Climate Change in physical systems or processes are exacerbated in areas where the environment has been damaged by humans for agriculture, mining or industrial purposes. This may lead to very highly contaminated "hot spots" and therefore of local food supply.

An illustrative example is the Aral Sea in Central Asia, which was once the fourth-largest lake in the world and has been one of the world's largest environmental disasters during the last 20 years. In the Aral Sea area, agriculture mis-management (e.g. cotton monoculture, over irrigation, pesticide abuse) and accelerated desertification due to both environmental degradation and climate change, have resulted serious contamination of soil, water and local foods with high levels of POPs and dioxins, leading to critical health and socio-economic impacts to local populations (Muntean et al., 2003).

3.5.4. Pesticide usage and residues in crops and the environment

Climate change as a driver will have different effects on the various types of plant pests. Based on studies of individual species, climate change may affect: pest developmental rates and numbers of pest generations per year; pest mortality due to cold and freezing during winter months; or host plant susceptibility to pests (FAO, 2005a; FAO, 2005b).

Farmers will need to find ways to control pests in the scenario of climate related change. The concept of Good Agricultural Practices (GAP) should, to the extent feasible in a given farming system, seek to include the three pillars of sustainability; GAP should be economically viable, environmentally sustainable, and socially acceptable; inclusive of food safety and quality dimensions (FAO, 2003).

Pesticides, both chemical and natural, that are presently commonly used, could in fact be no longer appropriate to the new agricultural scenario (climate, plant, environment). For instance, many pesticides have limited activity in dry conditions (Muriel et al., 2001), probably necessitating higher dose levels or more frequent applications to protect crops. On the other hand there is some evidence of faster degradation of pesticides due to higher temperatures (Bailey, 2004).

Integrated pest management (IPM) programmes serve to respond to problems associated with established pests. These initiatives build on lessons learned in countries including on the impact of changing crop-pest relations caused by cropping intensification, expansion of cropped areas, new crops and introductions of crops, pest introductions, and pest population dynamics and evolution. All these factors are influenced by climate variability and change and will need to be re-assessed to adapt to the impacts of new climatic conditions.

The current trajectory for warming and more extreme and unpredictable weather could have catastrophic effects on agricultural yields in the tropics, subtropics and temperate zones. Disease outbreaks could take an enormous toll in developing nations, and overuse of pesticides could breed widespread resistance among pests and the virtual elimination of protective predators (Rosenzweig, Yang, Anderson, Epstein, & Vicarelli, 2005). It is projected that warming and increased precipitation and accompanying diseases would increase the use (and costs) of pesticides for certain crops such as corn, cotton, potatoes, soybeans and wheat (Chen & McCarl, 2001). This has already happened in Brazil in when excessive rains in 2004 favored the development soybean rust leading to an increased level of fungicides used to control the disease (Rosenzweig et al., 2005).

Climate related changes in ecological conditions, increased crop pests, suitability of new areas to potential quarantine and unpredictability may all together lead to the misuse and/or abuse of pesticides usage. This may threaten the health of poor farmers, may contribute to environmental contamination with pesticide residues and may lead to increased residues in crops.

3.5.5. Veterinary drug use and residues in foods and the environment

Climate change may result in changes in the incidence of food-borne zoonoses and animal pests and possibly in increased use of veterinary drugs (FAO, 2008a). New diseases in aquaculture could also result in increased chemicals use. Consequently, there may be higher and even unacceptable levels of pesticide and veterinary drugs in foods (FAO, 2008a).

Climate change will be especially important to vector-borne diseases and macroparasites of animals and may also result in new transmission modalities and changes in host species. Changes in species composition and interactions will augment the emergence of unexpected events, including the emergence of new diseases and pests. While most developing countries are already subject to an enormous disease burden, both developing and developed countries will be subject to newly emerging diseases (FAO, 2008b).

Concerns associated with aquaculture in a warming environment include a greater susceptibility to disease, introduction of pathogens and antibiotic-resistant pathogens, heavy use of antibiotics and environmental contamination with pesticides (Shriner & Street, 2007).

Countries' attempts and plans to implement good animal husbandry and good aquaculture practices may be challenged by climate variability and change, particularly in developing countries, where frequently these practices are already difficult to implement and biosecurity measures are not in place. Risk assessments, protocols for use of veterinary drugs, pesticides, and/or establishment vaccination programmes will have to be re-assessed in view of the new challenges to animal health management derived from climatic variability. This together with the implementation good husbandry, aquaculture and veterinary practices will prevent the misuse of veterinary drugs and chemo-therapeutants in animal farming and aquaculture settings and limit the risks of unacceptable residues of veterinary drugs in foods and discharge of chemo-therapeutants and pesticides into the environment.

3.6. Emergency situations

According to the Intergovernmental Panel for Climate Change (IPCC) 4th assessment report, climate change is altering disaster risk patterns in three main ways:

- increase in frequency and intensity of extreme events, such as more frequent extreme temperatures and heavy precipitation, more intense tropical cyclones and expanded areas affected by drought and floods;
- changes in geographical distribution of areas affected by hazards;
- increase in vulnerability of particular social groups and economic sectors due to sea level rise, ecosystem stress and glacier melting.

By 2020, between 75 and 250 million people are projected to suffer increased water stress in sub-Saharan Africa and by 2080, 2–7 million more people per year, will be affected by coastal flooding (Yohe et al., 2007).

3.6.1. Increased frequency of climate related emergency situations

During the past 20 years, the number of recorded disasters has doubled from approximately 200 to more than 400 per year. Disasters caused by floods are more frequent (from about 50 in 1985 to more than 200 in 2005) and damage larger areas than they did twenty years ago. Current trends indicate a future where extreme climate variability and its consequences are likely to become the norm (Center for Research on the Epidemiology of Disasters (CRED), 2009).

Data from the CRED show that disaster frequency appears to be increasing, from about 100 events per decade in the 1900–1940, to 650 per decade in the 1960s, to 2000 per decade in the 1980s. By the 1990s this number had reached almost 2800 events per decade (CRED, 2007). The number of reported climate related disasters (e.g. droughts, floods, wind storms, forest fires, etc.) significantly increased from an average of 195 per year from 1987 to 1998 to an average of 365 per year from 2000 to 2006 (CRED, 2007).

Of the 262 million people affected annually by climate disasters between 2000 and 2004, more than 98% lived in developing countries (CRED, 2007). Climate variability is expected to result in more frequent and extensive disasters, with the most severe consequences on the food and water security, safety and livelihoods of vulnerable coastal and agriculture dependent populations.

Climate change related droughts and environmental degradation has been associated with war and other forms of conflict leading to major humanitarian and food crisis (UNEP, 2007). By increasing the scarcity of basic food and water resources, environmental degradation increases the likelihood of violent conflict (LEAD, 2006).

3.6.2. Food safety, natural disasters and humanitarian crises

During or following natural disasters, such as the cyclone in Myanmar 2008, the earthquake in China, the tsunami in South East Asia 2005, or the hurricanes in New Orleans in 2005, food in affected areas may become contaminated with dangerous microbiological and chemical agents. Consequently, populations are at risk of outbreaks of foodborne diseases, including hepatitis A, typhoid fever and diarrhoeal diseases, such as cholera, dysentery, norovirus infections and to the exposure to toxic chemicals through contaminated foods and water.

Climate related increasing frequency and severity of droughts and the consequent loss of livelihoods is a major trigger for population movements that are leading to major humanitarian crisis. The UN projects that there will be up to 50 million people escaping the effects of environmental deterioration by 2020. Forced migration frequently results in extreme stress, food and water emergencies, malnutrition, diarrhoea, limited access to medical care, all of which contribute to ill health. Poor health status leads to increased susceptibility to both microbiological and chemical food hazards and associated diseases.

Food safety risks associated with natural disasters and emergencies are mainly linked to unsafe food storage and cross contamination from the environment or from people during food handling and preparation. In many cases cooking may be impossible in emergency situations due to the lack of electricity, facilities or fuel. Poor sanitation, including lack of safe water and toilet facilities, and close personal contact can compound the risks of illness among these already susceptible groups.

The risk of infectious disease following flooding in high income countries is generally low, although increases in respiratory and diarrhoeal diseases have been reported after floods (Manuel, 2006). An important exception was the impact of Hurricanes Katrina and Rita in the USA in 2005, where contamination of water supplies with faecal bacteria led to many cases of diarrhoeal illness and few mortalities (Manuel, 2006).

3.6.3. Food safety measures in emergencies

When natural disasters strike, food safety is a crucial public health concern that has been too often neglected. Under the conditions that may occur during and after natural disasters and emergencies, the following issues require immediate attention (WHO, 2005b):

- preventive measures to assure food safety;
- inspecting and salvaging food;
- provision for safe food and water;
- recognition and response to outbreaks of foodborne disease;
- food safety education and information provided to affected populations.

To be able to effectively carry out these functions during an emergency situation requires the involvement of various groups who are aware of their roles and trained and equipped to execute them. It also requires a high level of coordination among all parties. These conditions can only be met if good emergency response plans are prepared and simulated proactively, and if there is the necessary local and national political will to support these plans.

Changing climate patterns have increased the urgency to invest in disaster risk reduction, preparedness and response plans. These plans should address food safety risks in the aftermath of natural disasters along the whole food chain. This requires assessments of national infrastructure and operational capacity, and the ability to merge these capabilities on an international scale, in an effort to build emergency preparedness and response capacity.

3.6.3.1. Scope of preparedness and response plans must consider the whole food chain. Agricultural production may be adversely affected by flooding associated with natural disasters. When crop fields have been contaminated or damaged, assessments should be carried out to establish the most efficacious measures which could be applied to reduce the risk of pathogens, hazardous chemicals, natural toxins, etc. (e.g. delayed harvesting, heat treatment), present in these crops and/or to assure appropriate disposal (FAO, 2005a; FAO, 2005b; WHO, 2005b). This includes the product in the food service sector. National emergency prevention and response plans should also have provisions for water and food distribution to those of greatest need.

Investigation of and response to suspected foodborne disease outbreaks is required in order to limit their spread. In addition, appropriate proper risk communication efforts can go a long way in minimizing risk.

4. Addressing food safety implications of climate change

There is still much to be understood about the food safety implications of climate change and variability, and awareness of possible new challenges is the first step to preparing to address them. However, despite substantial uncertainty in view of climate change, countries can proactively promote the strengthening of existing food safety management programmes with the hope that these efforts will provide a basis for action to address emerging risks. A summary of the adaptation strategies to address the impacts of climate change and variability on food safety is presented in Table 2.

4.1. Foodborne disease including zoonosis

Strategic and effective food safety management requires understanding microbiological hazards and how their presence in foods can be prevented or maintained within tolerable levels.

Improving the ability to understand and to control emerging microbiological hazards at all stages of the food chain will require efforts in a number of key areas including mathematical modeling; application of new scientific tools to improve the ability to characterize complex microbial communities; improved epidemiological surveillance; new tools for monitoring foodborne pathogens and disease; strengthened animal health surveillance; and improved coordination among food safety, public health and veterinary health services.

4.1.1. Predictive models

There are only a few time studies that have addressed foodborne diseases in view of climate change. Salmonellosis and campylobacteriosis have been studied in the context of climate change in 15 countries from Europe, Canada Australia. For example, Fleury et al. (2006) used time series analysis along with epidemiological data to predict the impact of ambient temperature on the risk of disease caused by three foodborne pathogens (*Salmonella*, *Campylobacter*, and *E. coli*) in Canada. Climate change scenario studies of the burden of foodborne diseases are complex and so far there is only one study on the burden of gastroenteritis – including Salmonellosis – in Australia (Bambrick et al., 2008).

Lobitz et al. (2000) used remote sensing data to indirectly measure *V. cholerae* behaviour as a function of ocean temperature and surface height, providing a means by which to predict conditions conducive to pandemic disease. Koelle, Pascual, & Yunus (2005) developed a complex theoretical framework for predicting the evolution of seasonal infectious disease dynamics based on a combination of host-pathogen dynamics, pathogen evolution and adaptation, and climate change. The use of mathematical models in microbial ecology is an emerging field, and though infrequently applied to climate change, this is a promising new direction for the field.

Molecular-based population genetics studies may also provide information on microbial population changes occurring in response to environmental stresses. Specifically nucleic acid sequence comparisons and genomics-based approaches applied to the characterization of complex microbial communities are promising approaches. These methods are also applicable to the study of microbial evolution, and the identification of virulence factor acquisition and expression as a function of changes in environmental exposures. When combined with geoinformatics (the combination of remote sensing, geographic information systems, and

Table 2
Adaptation strategies to address the impacts of climate change and variability on food safety and existing international initiatives.

Adaptation strategies		Initiatives
Intersectoral coordination	Public health, veterinary, food safety and environmental health services	Biosecurity approach
Integrated surveillance and monitoring	Foodborne diseases, animal diseases, microbiological and chemical food contaminants, veterinary drugs and pesticides residues, etc.	One Health approach Global Environmental Monitoring System for chemical contaminants
Risk assessment and predictive modeling	Emerging microbiological risks and zoonosis, chemical risks, fungal growth and mycotoxins; Harmful Algal Bloom (HABs) and marine toxins	FAO/WHO Risk Assessment work (JEMRA, JMPR, JECFA) Intergovernmental Oceanic Commission (IOC) – harmful algal bloom program
Improved detection methods	Research to develop tools for rapid detection of pathogens, microbiological and chemical contaminants, Biotoxins (marine toxins and mycotoxins)	Application of Biotechnology and Nanotechnology
Good practices	Food safety, agriculture, livestock and aquaculture production sectors	Good Hygiene Practices Good Agriculture Practices Good Husbandry Practices Good Aquaculture Practices Good Veterinary Practices
Risk management guidance	Food contaminants, animal health, plant health, etc. Mycotoxins HABs and fisheries safety	FAO Food-Chain Crisis management framework FAO Worldwide mycotoxin regulations for food and feed FAO/IOC/WHO Biotoxin risk management plans
Emergency preparedness and response	Agriculture sector Human and Veterinary Public Health Services	EMPRES-Food Safety INFOSAN

statistical modeling for the characterization of spatial distributions and relationships), these shorts of approaches may aid in the modeling of the distribution and spread of pathogens as a function of climate change.

4.1.2. Surveillance of foodborne diseases and zoonosis monitoring

There is a need for improved epidemiological surveillance for early identification of emerging food and water-borne diseases and for monitoring of zoonosis and other animal diseases. Large public and veterinary public health initiatives have been implemented over the last decade in the developed world. While these have not answered all our questions, they have provided much needed preliminary data about the prevalence of foodborne diseases, zoonosis and other animal diseases and trends in their annual incidence. Ideally, a global approach to epidemiological surveillance of foodborne and zoonotic diseases should be taken. Of particular importance is the rapid investigation of unusual outbreaks, with consideration of the potential for climate-related impacts in the appearance of such outbreaks. In addition, human and veterinary public health systems must be able to mobilize and respond quickly to emerging and re-emerging infectious foodborne diseases and zoonosis.

Ideally, epidemiological surveillance should have a correspondingly strong laboratory component. While pathogen detection methods are widely used in the clinical realm, their use in food and environmental applications is complicated and time consuming due to continued reliance on cultural enrichment. For non-culturable agents (e.g., noroviruses), detection is not even possible using these methods. Although nucleic acid amplification techniques are increasingly used, small assay volumes (several microliters) relative to large samples sizes (25 g, or 1 l) means that detection assays must be preceded by some sort of cultural enrichment. There is a clear need to focus research efforts on the development of culture independent rapid and sensitive methods to detect pathogens in complex sample matrices in near real time. This inherently means that target agents will need to be concentrated and purified from the sample matrix prior to detection. An ideal method would be rapid (results in a few hours), easy, inexpensive, field deployable, and provide enumerative results.

In the absence of truly rapid methods for pathogen detection, microbiological indicators are often used. These serve as easy-to-detect surrogates, usually for the presence of pathogens associated with fecal contamination. Historically, fecal coliforms or generic *E. coli* have served in this capacity. While these have been, and continue to be useful for some screening purposes, they are not always appropriate. Alternative indicators have been proposed but unfortunately, none of these are ideal and few have been thoroughly evaluated. In the absence of truly effective microbiological indicators, it will be extremely difficult to monitor the impact of global climate change on the transmission of several of the important foodborne pathogens.

4.1.3. Improved coordination among public health, veterinary health, environmental health and food safety services

Human, animal and environmental health are invariably interrelated. Countries such as Denmark have been promoting the application of integrated surveillance approaches to address human health, animal health and food safety (FAO/WHO, 2004). Strengthened communication and cooperation among professionals in these areas is particularly valuable as we seek to predict, recognize, and mitigate the impact of global climate change on infectious disease, including foodborne illness. Promotion of such cooperation worldwide would result in holistic, multi-disciplinary solutions to difficult problems for which a single discipline does not have an answer. In this context the "One World One Health" concept it is being promoted at the international level.

4.2. Mycotoxin contamination

The real problem with developing a strategy for reducing mycotoxin levels in food, whether for the present or for some potential worsening of conditions due to climate related changes in the future, is not in formulating the strategy but rather in implementing it. Chronic exposure, arguably the most important form of exposure, is subtle and the connection between cause and effect is difficult to substantiate so authorities move reluctantly. Implementation requires significant technical and financial capacity and at the same time, because mycotoxins are often seen as a 'theoretical' risk, it is sometimes difficult to foster the political will to act. Some of the points discussed below are ably considered for aflatoxin by Strosnider and et al. (2006).

4.2.1. Prevention of mycotoxin contamination

Complete prevention of mycotoxin occurrence is not feasible because mycotoxins at some level are a natural consequence of plant and fungal interaction. The aim is to prevent the occurrence at levels that might cause harm. To formulate a prevention strategy, the aetiology of toxin contamination must be ascertained in order to focus efforts to maximum effect. This often requires applied research which presupposes investment in the technical facilities and in the human resources to support such work. This science-based approach to developing risk-based mycotoxin prevention and control programmes has shown promising results (FAO, 2006).

4.2.2. Monitoring and predictive modeling

Monitoring can take many forms, including detection of markers or metabolites in populations in order to have a measure of exposure to toxins and it also refers to monitoring of mycotoxins in commodities or the environment. Monitoring data can contribute to the identification of an emerging problem; it can also provide feedback on the efficacy of "Good practice guidelines" and support risk assessment efforts to establish science-based maximum limits for contamination. Mathematical models have been proposed to use a combination of meteorological and insect population data for the prediction of mycotoxin outbreaks (De La Campa, Hooker, Miller, Schaafsma, & Hammond, 2005; Hooker & Schaafsma, 2005).

4.2.3. Maintenance of strategic food stocks

Food insecurity and hunger can lead to increased consumption of unfit food so by maintaining stocks of staple foods, of good quality, in secure storage facilities, this eventuality can at least be forestalled in an emergency. This is, of course, costly and requires careful attention to food quality and safety management particularly in relation to control of incoming stocks, 'first-in-first-out' storage management, and monitoring of storage conditions.

4.2.4. Agricultural policy and public information review

Mycotoxins are not generally understood by the public and as an essentially invisible threat are difficult to publicize effectively. Nevertheless, informing the public as to the risks of exposure and the nature of the food that carries these risks might help to reduce use of or trade in substandard food in times of need.

Climate change may make production of currently preferred crops difficult in some areas posing an obvious food security problem. Authorities could respond by encouraging production and consumption of alternative crops. Before this stage is reached, however, development and implementation of revised guidance on GAP or IPM programmes for problematic crops may improve performance and reduce mycotoxin risks. Introduction of new crop varieties or establishment of replacement crops are also likely to be elements of a food security strategy. It should be noted that the introduction of new crop varieties could fundamentally alter the dynamics of the crop's association with fungi. There have been reports of the possible role of biotechnology in the development of crops that can grow under marginal conditions (resistance to drought, salinity and insects) (Thomson, 2008). Making use of new technologies to address challenges presupposes the capacity to assure that they do not pose unacceptable risk to consumers or to the environment.

4.3. Harmful algal blooms and fishery product safety

The apparent increase in the occurrence of HABs and the recognition that changes in climate may be creating a marine environment particularly suited to HAB-forming species of algae underline the need for governments to ensure that existing risk management measures are adequate and are in line with international recommendations. Countries are encouraged to implement integrated shellfish and micro-algal monitoring programmes, as part of Marine Biotoxin Management Plans to strengthen risk management capability and to enhance consumer protection (FAO/IOC/WHO, 2005).

4.3.1. Predictive modeling

Improved capacity to predict HABs is important for more effective risk management and prediction of HABs depends on modeling exercises as well as an understanding of their ecology.

There is much ongoing research to improve our understanding of the factors that influence population dynamics of harmful algae. Until recently, most research on HABs had been conducted at the local scale, but several national and international programmes studying and monitoring the ecology of HABs now exist (Glibert et al., 2005). The international dimension is important for understanding and addressing the global impact of climate change on HABs.

Micro-algal monitoring coupled with operational oceanographic, meteorological, and remote sensing data, including modeling and other measurements are being used in the prediction of HABs. Traditional approaches, such as microscopic examination and analysis of toxins, resulting in species level of identification are unsuitable to real-time observation; however, new techniques and observational strategies for HABs are emerging and evolving.

HAB prediction is complex as it includes conceptual descriptions of ecological relationships and statistically based empirical models as well as numerical models. Predictions depend on observations which provide both input to models as well as data for model validation and error prediction (Barin et al., 2005). The effects of climate related changes increase the complexity of the system (as described in Section 3.4) and underscore the need for continued effort and international cooperation in this field.

4.3.2. Other risk management guidance

Improved capacity to predict HABs is an important risk management tool but other tools are needed as well. While these are not specific to climate change, as mentioned earlier the increased likelihood of biotoxin contamination events makes it worthwhile to focus attention on these requirements. The Joint FAO/IOC/WHO (2005) ad hoc Expert Consultation on Biotoxins in Bivalve Molluscs (FAO/IOC/WHO, 2005) recommended that, among other things, member countries be encouraged to generate more toxicological data (with studies conducted according to OECD guidelines) and that member countries be encouraged to improve and validate toxin detection methods in shellfish.

4.4. Environmental contaminants and chemical residues

Section 3.5 addresses the impact of climate change and variability on environmental contaminants and chemical residues in the food chain. To ensure the safety of foodstuffs, efforts are required in a few key areas to address these impacts.

4.4.1. Research priorities and data needs for developing predictive models

Basic information is required on the impact of climate change and variability on the fate of chemical contaminants, pesticides and other chemo-therapeutants in the environment. Impacts of ocean warming and acidification on the bioaccumulation of contaminants in aquatic species and on the structure and distribution of food webs, needs more research from the physical–biochemical point of view and the geographical distribution of aquatic species. Few studies have investigated the impacts of future climate change scenarios on aquatic biota and there is a need for data on future trends in aquatic primary production, nutrient supply and temperature sensitivity and on the combined response to elevated CO_2 and climate change of diseases, pests, weeds (Easterling et al., 2007).

4.4.2. Monitoring programmes

Integrated monitoring and surveillance of: (i) water, soils and foods for contaminants and chemical residues, (ii) crops for pesticide residues (iii) animal products for veterinary residues and (iv) emerging animal and human diseases is essential to address climate related environmental changes. The data generated may be used in the identification of emerging problems and food contamination trends and may contribute to risk assessments.

4.4.3. Good agricultural, animal husbandry, aquaculture and veterinary practices

These practices ensure the safety and quality of agricultural, aquaculture and animal products. They may need to be adapted or revised in light of changing climatic conditions. In relation to good veterinary practices, the appropriate use of veterinary drugs and chemicals in terms of safety, quality, amounts, frequency and timing and withdrawal times, are particularly important in a changing environment. The agriculture and sector offers multiple opportunities for climate change mitigation and environmental protection through the implementation of good animal husbandry and agriculture practices. Green house gases emissions can be reduced through improved diets can reduce enteric fermentation, improved manure management and biogas. Water pollution and land degradation can be tackled through better irrigation systems, fertilization schemes, better management of waste, improved animal diets that increase nutrient absorption (LEAD, 2006).

4.4.4. Data exchange

Good data exchange mechanisms are required at both national and international level. These should cover the distribution of animal and plant diseases, pests, ecological conditions including climate, and associated usage of pesticides, veterinary drugs and chemo-therapeutants will be needed to enable risk assessment, prevention, monitoring and control.

4.5. Emergency situations

The need to address food safety management in emergency situations is not specific to climate change. However the expected increase in frequency of extreme weather events renders the need for early warning systems and disaster preparedness in general more urgent.

The humanitarian implications of the increasing frequency and intensity of extreme weather events are significant, particularly from more frequent and intense storms, coupled with rising sea levels increasing the risk of flooding. Humanitarian organizations will require improved information about changing extremes in order to better manage changing risks and to deal with uncertainty.

4.5.1. Preparedness for emergencies

In light of the above, countries should review/develop food safety emergency plans as well as review and update other disaster/emergency plans to ensure adequate consideration of food safety management and veterinary public health issues in those situations. Developing and ensuring the capacity to implement such plans may require investment in trained human resources and in facilities.

At international level priorities for action include strengthening preparedness for effective response through:

- Expanded contingency planning, especially in areas prone to flood, windstorms or drought, and promotion of prevention and adaptation in the rehabilitation phases.
- More flexible funding mechanisms at the international level that allow development and humanitarian resources to be invested in preparedness.

The FAO is in the process of streamlining its prevention and management framework for food-chain crisis to ensure effective bridging between early warning, preventive actions and response to threats in the food chain. An integral component of this streamlining is the extension of the FAO EMPRES (Emergency Prevention System for Trans-boundary Animals and Plant Pests and Diseases) programme to also cover food safety. Its primary purpose is the prevention and early warning of food safety emergencies through improved food safety intelligence.

EMPRES-Food Safety will be closely interlinked with the International Food Safety Authorities Network (INFOSAN) and will focus on alerting members of imminent food safety threats based on credible indicators. EMPRES-Food Safety will act as radar to detect and analyze signals such as changes in plant pest and disease patterns, changes in food consumption trends, alterations in climate or shifts in cropping patterns. EMPRES-Food safety also provides assistance to countries to establish national plans for managing food safety emergencies and building their capacities to implement such plans.

4.5.2. Development of tools for rapid detection or removal of contaminants

Tools for rapid foodborne pathogen detection would be an important asset for food safety management in emergency situations (see Section 3.6).

Developments in technologies that could lead to simple and inexpensive removal of chemical and microbiological contaminants from water should be closely followed as such tools would also greatly facilitate improvements in food hygiene management in emergencies.

Such tools are under development notably these are both areas where nanoscience and nanotechnologies are expected to have considerable impact on food safety.

5. Conclusions and recommendations

Existing guidance to strengthen the essential elements of food control systems (i.e. coordination and management, legislative framework, surveillance, monitoring, laboratorial and inspection services, and education, information and communication), (FAO, 2003) remains valid in the face of additional challenges that may be posed due to climate change related phenomena. In fact, these challenges highlight the need for many countries to intensify their efforts to implement programmes of food safety management that are in line with FAO/WHO guidance.

The discussions in Sections 3 and 4 point to several common themes that deserve particular attention in ensuring that emerging risks are recognized as early as possible and that countries are prepared to respond promptly to these. These cross-cutting issues and recommendations are outlined below.

5.1. Interdisciplinarity

Assuring food safety is a complex issue as it involves considerations from pre-production through to final home preparation of the food product. Recommendations on food safety management emphasize the need for broad input and coordination between all sectors involved in the "farm to fork" food chain, even though this remains a challenge in many countries. Recognizing, understanding and preparing for the impacts of climate change further highlight the need to promote interdisciplinary approaches to addressing challenges affecting food safety given the inter-relationships among environmental impacts, animal and plant health impacts and food hygiene. These inter-relationships are further complicated by the broader public health implications of climate change as well as the food security implications.

5.2. Application of good practices

Principles of Good hygiene practices, Good agricultural practices, Good animal husbandry practices, Good veterinary practices, Good aquaculture practices, etc. remain the cornerstone of food safety management strategies to address challenges posed by climate change. Guidance in applying these principles may have to be adjusted as a better understanding develops regarding changes in the occurrence and prevalence of chemical and microbiological hazards as well as insects and other pests and their vectors, as affected by climate change and other factors.

Developing sound and practicable codes and guidelines may in some cases require applied research to better understand the new "dynamics" and to evaluate different approaches for controlling the problem.

As new information becomes available regarding the impact of climate change on food safety hazards, governments and industry and consumer associations will play an important role in reviewing and updating as necessary current guidance. In many developing countries the main challenge remains that of developing a policy framework that helps small and lesser developed businesses to overcome constraints and encourage founding good practice programmes (FAO/WHO, 2006).

5.3. Surveillance and monitoring – human, animal, food and environmental health

Surveillance is a critical component of public health and is essential not only for the early identification of emerging diseases and trends but also for resource planning and measuring the impact of control strategies. A global approach to epidemiological surveillance is necessary that will entail collaboration between human, animal and environmental health professionals. Of particular importance is the rapid investigation of unusual outbreaks. This is essential at both national and international level. The International Health Regulations is an example of a framework for the coordination of the management of events that may constitute a public health emergency of international proportions, and will improve the capacity of all countries to detect, assess, notify and respond to public health threats.

Integrated monitoring and surveillance of human and animal diseases, food contamination and environmental health is critical for the early identification of emerging problems and changing trends. While monitoring and surveillance programmes are currently implemented in many countries they may need to be reviewed and amended as necessary to address emerging hazards arising from global climate change. The data generated from these programmes contribute significantly to predictive modeling and risk assessments and should be shared readily both at national and international level. EMPRES-Food safety will play a major role in analyzing available data so as to predict, identify and prioritize potential and imminent food safety threats and advise on appropriate intervention measures to protect human health and preserve food safety.

5.4. Risk assessment

Risk assessment provides the scientific basis for the development and adoption of food safety standards and for guidance on other food safety measures. Climate change may give rise to emerging food safety risks that influence priorities for risk assessment. For example, if occurrence of multiple mycotoxins becomes more common in crops, it may become important to carry out risk assessments that adequately consider the combined effect of the toxins in determining maximum limits.

A number of Joint FAO/WHO expert bodies have been set up to carry out risk assessments on food additives, food contaminants, pesticide residues, veterinary drug residues and microbiological hazards. Other Joint FAO/WHO ad hoc expert committees are set up to deal with other emerging issues as they arise. FAO and WHO member countries can influence the prioritisation of risk assessment work carried out at international level according to clearly established criteria (FAO/WHO, 2007). In the case of emerging hazards related to the impact of climate change, member countries could have access to risk assessment advice.

Apart from the question of the availability of international risk assessment mechanisms it is important to emphasize the need to build the capacities of experts in developing countries to fully understand how these assessments are carried out so that they can make informed decisions on their applicability to the local context in light of new data coming out of their own monitoring and surveillance programmes. FAO, in collaboration with many international, intergovernmental and governmental bodies, has supported the development of a standardized training programmed to assist countries in understanding and carrying out GM food safety assessments (FAO, 2008a; FAO, 2008b; FAO, 2008c).

5.5. Predictive modeling

Currently there are no scenario-based projections of the impact of climate change on food safety systems. Predictive models are currently being developed (along with other tools such as operational oceanographic, meteorological, and remote sensing data) by the marine sector for the prediction of Harmful Algal Blooms (Edwards et al., 2006). These tools could be used by other sectors to predict the probability of global climate change on ecological systems and emerging food hazards, animal and plant health risks. The use of mathematical models in microbial ecology is an emerging field, and though not yet applied to climate change, this is a promising new direction for food safety issues (FAO, 2008c).

Predictions depend on the quality and quantity of available data; therefore, international collaboration is essential to ensure that appropriate data are collected and good models are developed. However, the impacts of climate change may manifest themselves slowly and the manifestations may be complex and highly uncertain. Climate related global changes increase the complexity of the climate-food system and this result in a high degree of uncertainty for the food sector (FAO, 2008c; Tirado, Cohen, Aberman, & Thompson, 2009).

5.6. Dealing with uncertainty

Uncertainties in predicting the behaviour of foodborne hazards in well characterized systems abound and such uncertainties are compounded when considering climate change. Indeed interactions at this level are numerous and complex since they are moderated by factors associated with the environment, natural resources, biodiversity, agriculture, fisheries, global trade, economic, social, demographic, technological development, health care environments, etc. (Tirado et al., 2009). Human factors, such as physiological adaptation, immunity, education and behaviour also influence the exposure of individuals and populations to climate-related hazards and their subsequent impacts. In addition, there are multiple underlying, indirect drivers of the impacts on food safety, which are at the same time, affected by climate change.

While predictive models are relevant to address the impacts of climate on food safety under certain circumstances (e.g. the seasonality of foodborne diseases), the large number of unknowns in this field requires clear consideration of uncertainty. Whenever social processes rather than physical processes are involved, determining causal models is difficult and sometimes impossible (Haines, Kovats, Campbell-Lendrum, & Corvalan, 2006). Nonetheless the lack of predictability should not restrict the development of candidate food safety strategies to respond to climate change threats in the short term. In the absence of good data and accurate predictions, uncertainty can be characterized by using appropriate methods that actually aid in the decision process as it has been done in the water sector (Groves, Knopman, Lempert, Berry, & Wainfan, 2008). In this context, uncertainty can be managed by establishing robust decision processes that produce satisfactory results in modifying food safety strategies in response to climate change. Careful attention to uncertainty analysis also provides transparency to the decision making process and identifies the areas in greatest need of future study.

5.7. Early warning and emergency response systems

Enhanced early warning systems are essential to reduce the risk to life and livelihoods of vulnerable people posed by climate change related natural disasters and emergencies. This requires good collaboration and communication between sectors (e.g. veterinary, food safety and public health) at national and international level.

Emergency preparedness is also essential. Countries should review/develop food safety emergency plans as well as review and update other disaster/emergency plans to ensure adequate consideration of food safety management issues in those situations.

5.8. Strengthened dialogue with the public

Food safety is ensured through the implementation of adequate control measures at every step along the food chain, i.e. from farm to fork. To ensure consumers play their role, it is important they are aware of the hazards associated with foods and the relevant control measures. Education of consumers is therefore essential to inform them of emerging risks related to a changing environment and governments have a role to play in this regard. For example, some hazards such as mycotoxins are not generally understood by the public and as an essentially invisible threat are difficult to publicize effectively. Nevertheless, informing the public about typical foods susceptible to mycotoxin contamination and the risks to public health might help reduce both the use and trade of substandard food in times of need. Consumers need to be informed of emerging risks related to climate change and variability and the ways to address them.

5.9. New technologies

Section 4 highlights a number of scientific and technological innovations that are expected to play a major role in helping to understand and to deal with the food safety challenges posed by climate change. Potential applications in the food and agriculture sector include: (i) genetically modified crops that are suitable for growth in areas most affected by droughts or floods, salinized soils etc.; (ii) new molecular biological methods such as nucleic acid sequence comparisons and genomics-based approaches to characterize complex microbial communities and their interactions; (iii) rapid pathogen and contaminant detection using novel techniques (including nanotechnologies); (iv) new filtration devices based on developments in nanotechnologies that can remove a range of chemical and microbiological contaminants from soils and water and eventually from foods, etc. (FAO, 2008c).

Clearly different countries have differing capacities to directly participate in the development of these scientific and technological applications but it is important for all countries to strive to remain updated with developments so that they can make best use of new opportunities and, perhaps, influence the prioritisation of research investments.

Attention must be paid to the need to develop capacities and mechanisms within countries to assess and manage any environmental or food safety risks that might be associated with various applications of these new technologies. As noted above, FAO/WHO has provided and continues to develop guidance on GM food safety assessments. FAO/WHO have hold an expert meeting on the potential food safety implications of nanotechnology applications in the food and agriculture sectors (2009).

5.10. Investment in scientific and technical capacities

A common theme in several of the above-listed issues is the need for applied research to provide a better understanding of problems and new approaches for dealing with them. The ability to use science to find solutions depends on prior investment in human resource development. In many developing countries there is need for more careful planning to encourage the development of the competence that they need to address pressing problems. In many cases, it is already possible to make better use of the available competencies at national level by encouraging linkages between government services, universities, private sector associations, etc.

Careful assessment of food safety capacity building needs by national authorities is also essential in order to make best use of training and education opportunities including through technical assistance from interested donors and international organizations.

5.11. International dimension

The whole issue of climate change in all of its dimensions is a global concern and international organizations have a major role in ensuring coordinated approaches to dealing with all aspects.

The need for sharing of data and information coming out of food safety and disease monitoring and surveillance and the role of international networks in facilitating this has been noted above. Regional or international cooperation on selected research areas of common interest would also allow better outputs for a given set of resources.

As new food safety risks emerge, the international community needs access to timely scientific advice to guide risk management choices. As climate change may be a factor leading to the emergence of food safety risks it is useful to consider ways in which the mechanism for provision of scientific advice could be made more responsive to increased and unscheduled demands for advice. The Joint Global Initiative for food related scientific advice (GIFSA) that was recently established by FAO and WHO should at least partly address this need. GIFSA is a mechanism to facilitate mobilization of funds in a transparent manner for the conduct of expert meetings on critical food safety issues requested by Codex and by FAO and WHO member countries.

The food safety challenges raised by climate related changes highlight the need for continued emphasis on food safety capacity building to developing countries. Coordination among donor agencies and international organizations providing technical assistance in this area remains a central.

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