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INVITED REVIEW

Environmental contaminants in foods and feeds in the light of climate change

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Abstract

Introduction Environmental contaminants are groups of unwanted, ubiquitous chemicals, found in food via weathering of the earth's crust, combustion (natural or anthropogenic), industrial uses or as unwanted bi-products of manufacturing processes. Evidence suggests that the climate is becoming hotter and more variable, resulting in rising sea levels, warmer oceans, more forest fires and more extreme events such as floods, storms, cyclones, droughts and landslips. *Methods* Sources of environmental contaminants into food or feeds are described. The impact of climate change on the formation, distribution or uptake of these contaminants is addressed with reference to the scientific literature. *Results* Climate change may result in increased atmospheric release and mobilization of environmental contaminants, an increased rate of mercury methylation, changes in biological systems and increased applications of contaminants to soils and crops from water re-use. Conversely, climate change policies, to reduce carbon emissions, are driving energy efficiencies, leading to reduced emissions of dioxins, polycyclic aromatic hydrocarbon and heavy metals. *Conclusion* Climate change is likely to increase human exposure to arsenic, cadmium, lead, mercury, dioxins, polycyclic aromatic hydrocarbons and polychlorinated biphenyls where food and feeds may be contaminated by forest fires, water re-use or increased methylation (mercury only). The extent of this change is yet to be quantified.

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Introduction

Evidence suggests the climate is becoming warmer, on average, and more variable, resulting in rising sea levels, warmer oceans and more extreme events such as floods, storms, cyclones, droughts, landslips and forest fires (Parry *et al*., 2007; Rosenzweig *et al*., 2007; Podur & Wotton, 2010). Such events have the potential to alter the concentration of unwanted environmental contaminants inadvertently found in food and feeds via their deposition or uptake, from air, water or soil, and thereby affecting human health. Climate change is the focus of much global attention with food safety in general, and agricultural chemicals in particular, the topic of recent publications (Boxall *et al*., 2009; Tirado *et al*., 2010). In this paper we extend the knowledge of the impact of climate change on environmental contaminants in food and feeds.

Environmental contaminants include brominated flame retardants [BFRs including polybrominated diphenyl ethers (PBDE) and others], dioxins and furans (PCDD/Fs), polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), heavy metals and arsenic. In contrast, pesticides and veterinary drugs are intentionally applied to crops or animals. However, growing concern with respect to degradation products of some of these latter compounds means these might also be considered within the context of environmental contaminants.

Climate change

It is not the intent of this paper to debate climate change. Rather, expert findings of climatic changes that may impact on environmental contaminants were drawn from the Intergovernmental Panel on Climate Change (IPCC) and the scientific literature. The IPCC is an intergovernmental body and network of climate change scientists and experts established by the World Meteorological Organization and the United Nations Environment Programme (UNEP) in 1988 with the mandate to provide an authoritative international statement of scientific understanding of climate change.

'Climate change' in our paper is based on the IPCC definition, i.e. 'any change in climate over time, whether due to natural variability or as a result of human activity' (Parry *et al*., 2007). Thus climate change may be due to natural processes such as solar changes and volcanic eruptions, and/or persistent human activities like vehicle use, farming and burning fossil fuels. We note that this usage of climate change differs from that of the United Nations Framework Convention on Climate Change, that excludes any changes to climate attributable to natural causes (UNFCCC, 1992; Parry *et al*., 2007).

There is international consensus of a number of climatic changes (IPCC, 2007). Global atmospheric concentrations of carbon dioxide have increased from a pre-industrial (before 1750) value of about 280–379 p.p.m. in 2005, largely due to fossil fuel use with a smaller contribution from a change in land-use. Methane and nitrous oxide levels have also increased from about 715 to 1732 p.p.b. and about 270–319 p.p.b., respectively, over the same time period, primarily due to changes in agricultural practice (IPCC, 2007). Global average air temperatures have increased by 0.74 °C in the 100 years from 1906 to 2005. The average ocean temperature has increased since 1961, mountain glaciers and snow cover have declined and the average sea level has risen by an estimated 0.17 m over the 20th century. Long-term changes are observed in arctic temperatures and ice, precipitation levels, ocean salinity, wind patterns and extreme weather events including droughts, heavy precipitation, heat waves and the intensity of tropical cyclones.

The impact of these changes include perturbation of natural biological systems, increased forest fires, mobilization of contaminants from poor storage containments, an increased need of water re-use and changing greenhouse gas emission policies.

Environmental contaminants, human health effects and sources into food

Establishing a reason for concern of exposure to a particular chemical and an adverse effect in humans is problematic because of the array of chemicals to which humans are exposed, often at very low levels, and the usual delay between exposure and evidence of symptoms. Furthermore, the organic environmental contaminants (BFRs, dioxins, PCBs and PAHs) comprise groups of compounds where individual chemicals have varying toxicities. This requires techniques for summing effects of individual chemicals within a group of contaminants. Because it is not usually considered as ethical to conduct human toxicity experiments, evidence of adverse human health effects from environmental chemicals is a compilation of epidemiological studies, case control and outbreak studies, animal and *in vitro* toxicological assessments and mechanistic studies. Evidence is often inconclusive for the reasons stated above and because of data gaps. In addition, an environmental contaminant may be associated with multiple adverse effects.

Human dietary exposure to environmental contaminants may occur from the consumption of plant foods contaminated by atmospheric deposition or the uptake from soils; foods of animal origin that have accumulated contaminants through the food chain; fish exposed to contaminants in the aquatic environment; and contaminated drinking water. Consideration of major contributing foods may inform the relative importance of different environmental sources, e.g. from atmospheric deposition or bioaccumulation in the food chain.

While not intending to be a comprehensive review, an understanding of the chemistry, uses and sources of the various environmental contaminants into food is necessary to assess the potential impact of climate change on these chemicals in the food chain. Human health effects, sources of release to the environment and major contributing foods for human dietary exposure to environmental contaminants are summarized in Table 1.

Arsenic is a grey metal-like element that occurs naturally in rock, soil, water and air. Elemental arsenic is used as an alloying element in ammunition and solders, as a lubricant and to strengthen lead batteries. Inorganic arsenic is primarily used as a wood preservative, but in response to human health issues, this application is declining

Table 1 Health effects, environmental release and major contributing food sources of environmental contaminants in food and feeds

Environmental contaminant	Adverse health effect	Sources of environmental release	Major contributing foods for human exposure	References
Arsenic	*Acute:* nausea, vomiting, diarrhoea, cardiovascular effects, adverse brain effects (encephalopathy) *Chronic*: dermal effects, numbness in hands and feet, skin, bladder and lung cancer	Natural weathering of rocks and soils Anthropogenic combustion of treated timber Manufacturing processes: timber treatment, agrichemicals, alloys, metal lubricant	Seafood, cereals, beverages, water	Vannoort and Thomson (2005a), ATSDR (2007b), Rose *et al*. (2010)
BFR	Liver toxin, immune and neurological effects, endocrine and thyroid disruption	Migration from commercial applications: electrical and electronic equipment, textiles, plastics, foams Anthropogenic practices: municipal incinerators, application of sewage sludge Accidental release from landfill	Oils, fats, fish, shellfish, meat, dairy products and eggs	Birnbaum and Staskal (2004), USEPA (2010)
Cadmium	Kidney and bone damage, caner	Natural weathering of rocks and soils Natural combustion: forest fires, volcanic eruptions Manufacturing applications: batteries, pigments for plastics, ceramics and enamels, stabilizers for plastics, plating on iron and steel, element of some lead, copper and tin alloys, by-product of mining, smelting and refining of zinc, lead and copper production Agricultural practice: impurity in phosphate fertilizers, sewage sludge	Shellfish, organ meats, leafy vegetables, potatoes, bread, cereals, beverages	Vannoort and Thomson (2005a, b), ATSDR (2008), Rose *et al*. (2010), Satarug *et al*. (2010)
Dioxins and dioxin-like PCBs	Skin lesions, cancer, endocrine disruption, immune, neurological and reproductive effects	Natural combustion: forest fires, volcanic eruptions Anthropogenic combustion: power generation, waste incineration, wood burning, crematoria, cement kilns, automotive exhausts Manufacturing processes: timber treatment, chlorine bleaching of pulp and paper, steel and smelting industry, chemical manufacturing. Leakage and accidental spills from reservoirs and factories	Fish, meat and dairy products	Liem *et al*. (2000), CAC (2006), Kulkarni *et al*. (2008), Boxall *et al*. (2009)
Lead	Hematological, gastrointestinal, cardiovascular, renal, neurological and reproductive effects, impaired metabolism of vitamin D (children)	Natural weathering of rocks and soils Manufacturing processes: component in pipes, solder, weights, storage batteries, ceramic glazes, paint and petrol, used as a radiation shield.	Beverages, vegetables, bread, cereals, sausages	Vannoort and Thomson (2005a), ATSDR (2007a), Rose *et al*. (2010)
Mercury	*Methyl mercury:* Impaired neurological development, impaired peripheral vision, disturbances in sensations, lack of co-ordination, impaired speech, hearing, walking, muscle weakness *Inorganic mercury*: skin rashes and dermatitis, mood swings, memory loss, mental disturbances, muscle weakness	Natural weathering of rocks Natural combustion: forest fires, volcanic eruptions Anthropogenic combustion: power generation, biomedical and municipal waste incineration, crematoria Manufacturing processes: mining and smelting, cement production	Fish and seafood	ASTDR (1999), USEPA (2009b)

Table 1 Continued

Environmental contaminant	Adverse health effect	Sources of environmental release	Major contributing foods for human exposure	References
PAHs	Cancer	Natural combustion: forest fires, volcanic eruptions Anthropogenic combustion: power generation, domestic heating, waste incineration, automotive exhausts Food processing: smoking, drying, cooking	Cereals and cereal products, fresh fruit, fruit products, meat and meat products, seafood and seafood products	EC (2002), EFSA (2008), Martí-Cid *et al*. (2008), Cirillo *et al*. (2010)
PCBs	Cancer, endocrine disruption, immune, neurological and reproductive effects	Migration from industrial applications: insulating fluids, components of fluorescent lighting, plasticizers in paints, plastics, rubber and cement products, stabilizing additives in flexible PVC coatings of electrical wiring and electronic components, pesticide extenders, cutting oils, reactive flame retardants, lubricating oils, hydraulic fluids, sealants (for caulking in schools and commercial buildings), adhesives, wood floor finishes de-dusting agents, water-proofing compounds, casting agents, vacuum pump fluids, fixatives in microscopy, surgical implants, in copy paper, kiss-proof lipsticks, chewing gum Leakages and accidental spills Illegal disposal Industrial incineration	Fish, meat and dairy products	ATSDR (2001), CAC (2006), DEFRA (2007), USEPA (2009c)

BFR, brominated flame retardants; PCB, polychlorinated biphenyls; PAH, polycyclic aromatic hydrocarbons.

[US Geological Survey (USGS), 2010]. Former pesticide, herbicide and insecticidal uses of inorganic arsenic are also declining [Agency for Toxic Substances & Disease Registry (ATSDR), 2007b]. Most foods contain some arsenic and it may accumulate in fish and seafood (Vannoort & Thomson, 2005b). High levels of arsenic are found in waters from certain geological areas and thermally active regions, e.g. arsenic is known to naturally contaminate groundwater and food such as rice or fish produced in parts of Bangladesh [World Health Organization (WHO), 2001].

BFRs are a group of chemicals used in electrical equipment, plastics, foams and fabrics to reduce fire-related injury and economic loss from preventable fires (Birnbaum & Staskal, 2004; D'Silva *et al*., 2004). BFRs comprise five major classes, namely, diphenyl ethers (PBDEs), brominated bisphenols, cyclododecanes, phenols and phthalic acid derivatives (Birnbaum & Staskal, 2004). The most studied of these are the PBDEs which are a group of more than 75 synthetic congeners with halogen substitution patterns analogous to the PCBs. Evidence suggests BFR levels have increased in the environment, wildlife and people over time [Birnbaum & Staskal, 2004; Hale *et al*., 2006; Hung *et al*., 2010; US Environmental Protection Agency (USEPA), 2010] although this may change with the cessation of production and use of the different PBDE formulations. Penta- and octa-BDE were phased out in Europe and the United States several years ago and deca-BDE will be phased out in the United States by December 2013 (USEPA, 2010). Use of alternative BFRs such as tetrabromo bisphenol A and hexabromocyclododecane is increasing as a result of decreasing use of PBDEs. BFRs are released to the environment as a result of production and manufacturing, by migration from commercial applications and from waste disposal practices. BFRs are widely dispersed through the atmosphere and bioaccumulate in the food chain. The major source of human exposure to BFR is from household dust with food accounting for only about 10% of human exposure (USEPA, 2010).

Cadmium is a chemical element and one of the components of the earth's crust and oceans (Rose *et al*., 2010). Cadmium is produced as a by-product of mining, smelting and refining industries and occurs as a natural impurity in phosphate fertilizers. Cadmium is traded globally as a metal and as a component in various products, particularly Ni–Cd batteries. Global consumption is expected to be static (USGS, 2010). Cadmium enters the food chain via natural soil sources, the application of fertilizer or sewage sludge to crops and from atmospheric deposition of volcanic ash, forest fires and industrial emissions (ATSDR, 2008). Because of a high rate of soil-to-plant transfer, cadmium is found in most foods (Vannoort & Thomson, 2005b).

Lead is a naturally occurring metal that occurs in the earth's crust and is used in a number of industrial applications, particularly the lead-acid battery industry, because of its high density, resistance to corrosion and low-melting point. Global lead consumption is predicted to increase owing to the growth in automotive and electric bicycle markets in China (USGS, 2010). Lead is ubiquitous in the environment, and food is the primary route of exposure for the general population (ATSDR, 2007a). The decreased use of lead solder in canned foods, lead in paint and as an additive to petrol has resulted in decreased lead levels in food in some countries (Vannoort & Thomson, 2005a). Lead accumulates in the body and can cause various adverse health effects. Of particular concern is impairment of intellectual and cognitive function of the foetus and child (ATSDR, 2007a).

Mercury is a chemical element and is distributed throughout the environment by both natural weathering of mercury-containing rocks, volcanic activity and forest fires or anthropogenic combustion and manufacturing activities (Rose *et al.*, 2010). Results of several studies suggest anthropogenic mercury emissions are about three times higher than pre-industrial levels (ATSDR, 1999). About half the global use of mercury is for the manufacture of vinyl monomer in China and eastern Europe and the future consumption of mercury is unclear (USGS, 2010). Mercury bioaccumulates in the food chain, such that large predatory species such as shark and swordfish contain higher levels of mercury than small fish species. Mercury exists in various forms. Both organic methylmercury and inorganic mercury can be ingested and cause adverse health effects in humans. Methylmercury is more toxic than inorganic mercury and first gained notoriety in Minimata, Japan after causing severe disabilities and death among people eating seafood contaminated through industrial mercury discharge (ATSDR, 1999; Takizawa, 2000).

PCBs are a group of over 200 chlorinated organic compounds intentionally manufactured until the 1980s for a multitude of industrial applications ranging from transformer fluids to chewing gum. Although manufacture was banned in many countries from the late 1970s, PCBs, like dioxins, are persistent in the environment with half-lives measured in decades, and may enter the food chain because of their former industrial uses (Fernandes *et al.*, 2004).

Polychlorinated dibenzo-*p*-dioxins (PCDDs) and dibenzofurans (collectively referred to as 'dioxins') are a large group of chlorinated organic chemicals. Of the 210 possible compounds, 17 have dioxin-like toxicity. Dioxins are released into the environment and enter the food chain, as a result of combustion that may be natural, or anthropogenic, as unwanted by products of manufacturing processes or from landfill/waste storage sites (Startin & Rose, 2003). Dioxins occur in the environment principally as a result of anthropogenic activities. Industrial emissions of dioxins peaked in the 1980s and active abatement policies have reduced emissions by up to 90% [European Commission (EC), 2009]. Regulation of industrial sources of PCDD/Fs probably accounts for a significant proportion of the gradual decrease in the amount of these compounds in the environment, and the consequent downward trend of concentrations in human milk (as a biomarker for human exposure) (LaKind, 2007).

PAHs consist of a large class of about 250 aromatic compounds containing two or more fused aromatic rings made up of carbon and hydrogen (Wilcke, 2000). The most studied and most toxic is benzo(a)pyrene, a known genotoxic carcinogen. PAHs are formed by incomplete combustion of organic matter that may be natural or due to human activities. Anthropogenic combustion of fossil fuels is considered the most important source of PAH inputs to the environment (Wilcke, 2000). Analysis of soil PAH profiles recently attributed the predominant PAH source in Poland to coal combustion, as the main energy source for industry and domestic heating in that country (Maliszewska-Kordybach *et al.*, 2009). PAHs can be widely distributed by atmospheric transmission and may enter the food chain from direct deposition onto crops (Maliszewska-Kordybach *et al.*, 2009). PAHs may also contaminate food from food processes such as smoking, drying and high temperature cooking (Rose *et al.*, 2007). Unlike the dioxins and PCBs, they are readily metabolized by most animals (except shellfish) and do not bioaccumulate.

Impact of climate change on sources of EC in food and feed

A change in climate over time may potentially alter the release, distribution and/or uptake of environmental contaminants into the food chain in a number of ways. Evidence of such impacts is an emerging area and data is yet limited (Table 2).

Flooding

Flood events can transport dioxins, heavy metals and hydrocarbons from a contaminated area to a non-contaminated one (Boxall *et al*., 2009). This was evidenced in the transfer of dioxins from contaminated soil deposited onto floodplains following flooding of the Elbe and Mulde rivers in central Europe in 2002 and in two river systems in the United Kingdom that flow through urban and industrial areas (Lake *et al*., 2005; Stachel *et al*., 2006). Elevated dioxin levels were found subsequently in milk from cows grazing the floodplains compared with barn fed or control pastures, demonstrating that allowing animals to graze on contaminated areas can represent a potential threat to food quality.

The floodwaters resulting from Hurricane Katrina illustrated the potential for chemical contamination from a variety of sources including leakage from damaged sewage treatment plants, oil refineries, chemical plants, storage facilities, poorly managed hazardous waste sites or mobilization from one contaminated area to another (Manuel, 2006). Elevated levels of arsenic, lead and PAH were detected in a proportion of the 1800 sediment and soil samples collected and analysed by the USEPA following the hurricane in 2005. The highest concentrations of arsenic were considered likely to have resulted from herbicide use in the vicinity. Localized PAHs found near a landfill site were indicative of landfill spillage and elevated levels of lead comparable to historical concentrations are thought to reflect the potential for flood events to mobilize environmental chemicals from one site to another (USEPA, 2009a).

Warmer oceans

Mercury is methylated to produce methylmercury in aquatic environments by microbiotic and chemical mechanisms (UNEP, 2002). Warmer oceans facilitate the methylation of

Table 2 Evidence of impacts of climate change on environmental contaminants in food and feeds

Environmental contaminant	Climatic event	Effect of climatic event	Impact on food safety	Relative importance to human exposure	References
Arsenic	Flooding	Translocation from contaminated sites to agricultural land	Potential uptake into pastoral foods	Infrequent localized impact on a major food source. *Low*	Tirado *et al*. (2010), USEPA (2010)
	Drought	Use of contaminated water for irrigation	Uptake into key crops (rice, wheat)	Regular impact on a major food source of many people. *Medium-high*	Dittmar *et al*. (2007)
Cadmium	Biological changes	Increased uptake/bioavailability	Higher concentration in the food chain	Regular localized impact on a minor food source. *Low*	Intwala *et al*. (2008)
Dioxins and dioxin-like PCBs	Flooding	Translocation from contaminated sites to agricultural land	Uptake into milk and milk products	Localized impact on a major food source. *Low*	Lake *et al*. (2005), Stachel *et al*. (2006)
	Forest fires	Increased formation of dioxins	Increased uptake via atmospheric deposition	Infrequent, wide dispersion to major food source. *Low*	
Lead	Flooding	Translocation from contaminated sites to agricultural land	Uptake into pastoral foods	Localized impact on a major food source. *Low*	USEPA (2009a), Tirado *et al*. (2010)
Mercury	Global warming	Increased Arctic algal growth	Increased concentration of Hg into fish	Major food source for Arctic people. *Medium-High*	Carrie *et al*. (2010)
	Warmer oceans	Increased methylation	Increased concentration of Hg into fish	Regular, widespread impact on major food source. *Medium*	Booth and Zeller (2005)
	Forest fires	Release of sequestered mercury from soil	Increased uptake via atmospheric deposition	Infrequent, wide dispersion to food sources. *Low*	Rosenzweig *et al*., (2007)
PAHs	Floods	Translocation from contaminated site to agricultural land	Uptake into pastoral foods	Infrequent, localized impact on a major food source. *Low*	USEPA (2009a)
	Forest fires	Increased formation of PAH	Increased uptake via atmospheric deposition	Infrequent, wide dispersion to major food source. *Low*	Rosenzweig *et al*. (2007)
	Warmer drier summers	Need to re-use water for irrigation	More contaminants applied to crops	Direct, frequent application to the food chain in localized areas. *Medium*	Al Nasir and Batarseh (2008)
PCBs	Global warming	Increased Arctic algal growth	Increased concentration of PCBs into food chain	Major food source for Arctic people. *Medium-High*	Carrie *et al*. (2010)
	Warmer drier summers	Need to re-use water for irrigation	More contaminants applied to crops	Direct, frequent application to the food chain in localized areas. *Medium*	Al Nasir and Batarseh (2008)

PCB, polychlorinated biphenyls; PAH, polycyclic aromatic hydrocarbons.

mercury. The subsequent uptake of methylmercury in fish and mammals has been estimated to increase by 3–5% for each 1 °C rise in water temperature (Booth & Zeller, 2005). This will potentially increase human dietary exposure to toxic methylmercury.

Biological changes

Evidence supports climate-related changes in natural biological systems (Rosenzweig *et al*., 2007). One outcome is the potential increase in the uptake of heavy metals and organic contaminants into the food chain by algae. Intwala *et al*. (2008) found that algae from the Great Lakes can use cadmium as a nutrient replacement for zinc, an essential trace element. The impact of this system change is to increase the bioavailability of cadmium in the food chain.

Arctic warming

Similarly, increased bioavailability was proposed by Carrie *et al*. (2010) who found concentrations of mercury and PCBs in burbot (*Lota lota*), a top predator Arctic fish, have increased significantly despite falling, or stable atmospheric levels. They postulate this increase is attributable to increased algal growth in a warmer climate, leading to increased uptake of mercury and PCBs from sediments (Carrie *et al*., 2010).

Increased forest fires

Warmer and drier conditions as a result of global warming were considered by the IPCC to be partly responsible for increased forest fires (Rosenzweig *et al*., 2007). A doubling of the area burned by forest fires by the decade 2040 was recently estimated for Ontario, Canada after taking account of fire suppression activities (Podur & Wotton, 2010). Because forest fires release sequestered cadmium and mercury in plants and soils, and result in formation of PAH and possibly dioxins (Kim *et al*., 2003; Turetsky *et al*., 2006; Galarneau *et al*., 2007; Biswas *et al*., 2008) the predicted increase in forest fires will potentially result in increased release of dioxins, PAH, cadmium and mercury to the atmosphere and thence into food.

Water re-use and irrigation

Warmer and drier summers will likely increase the demand and need to re-use water for crop irrigation. Re-use water for crop irrigation may lead to more contaminants being applied to soil/crops. Al Nasir and Batarseh (2008) found increased concentrations of PAHs and PCBs in wastewater treated soils and uptake into plants grown in these soils compared with groundwater treated sites. The uptake by plants varied for different plant types (Al Nasir & Batarseh, 2008).

Groundwater naturally high in arsenic is used widely for rice irrigation in Bangladesh and West Bengal during the dry season. Accumulating levels of arsenic in the soil are partly offset by mobilization from monsoon flooding (Dittmar *et al*., 2007; Roberts *et al*., 2010). Increased dry periods resulting from climate change has the potential to exacerbate increasing soil concentrations and thence lower yields and higher levels of arsenic in rice grown in these arsenic high areas (Khan *et al*., 2010).

Future decades may or may not see climate change, but will almost certainly see an increase in global population, changes in land-use, a shift in economic power towards China and Asia and increased demands on water. It is the combined impact of these factors that we will need to address to ensure safe food with respect to environmental contaminants.

Predicted impacts in terms of human exposure

Climate change effects may be localized, in the case of flooding or irrigation, or more widespread, as may be argued for increased Arctic algal growth, atmospheric dispersion from forest fires or an increased rate of mercury methylation in warmer oceans. Climatic change events may be infrequent in the case of flooding and forest fires, or more regular, as for effects from warmer oceans, less ice cover in the Arctic or the need for re-used water for irrigation. The climatic event may affect a food source of more or less significance to human food and feeds. An increase in environmental contaminants in fish, that is a staple food for Arctic peoples, or an elevated level of arsenic in rice in Bangladesh, will potentially have more impact than an increased level of cadmium in a freshwater lake. Thus impact will be the product of frequency, affected area, affected food as well as intensity of the effect. An impact ranking of climatic events with respect to environmental events on a scale of low to high that takes these factors into account is shown (Table 2). On this basis, the areas of most concern are arsenic in areas of high arsenic in groundwater that is used for irrigation; mercury, PCBs and any other contaminants entering the Arctic food chain via Arctic algae; PCBs and PAHs and any other contaminants entering the food chain as a result of re-used water for irrigation.

Climate change policies, to reduce carbon emissions, are driving energy efficiencies, leading to reduced emissions of dioxins [EC, 2009; American Chemistry Council (ACC; Chlorine Chemistry Division, 2010]. Given that fossil fuel combustion is the major source of PAH input to the environment (Wilcke, 2000; Maliszewska-Kordybach *et al.*, 2009) and that dioxin emissions are also related to fuel consumption (EC, 2009), policies that reduce fossil fuel combustion, with the intention of reducing carbon emissions, will also reduce the release of dioxins and PAHs to the environment. In this way climate change is predicted to have a beneficial impact on the concentration of these contaminants into food and feeds.

Volcanic eruptions cause short-term climate changes and contribute to natural climate variability by reducing transmission of solar radiation and increasing absorption of terrestrial radiation. The net effect is one of cooling (NASA, 2010). While it is not obviously apparent if, or how, climate change may impact on the occurrence of volcanic activity, volcanic eruptions themselves are a reported source of dioxins, PAH, mercury and cadmium to the atmosphere and hence into the food chain. Thus they have an impact on environmental contaminants though we postulate this is not an impact of climate change.

The situation is only emerging and the ranking presented is limited by data gaps. Most apparent is the lack of evidence of heavy metals other than mercury released by forest fires, heavy metal contamination from reused water, the magnitude of increased methylation in the ocean, the impact of cadmium from potential increased fertilizer use and any evidence of the impact of climate change on BFRs. Of the anthropogenic sources of environmental contaminants, only lead would appear to be increasing, although a shift in industrialization from North America and Europe to India and China raises uncertainty about future usage and production.

Conclusions

Evidence of the impact of climate change on environmental contaminants in food and feeds is an emerging area and we recognize that the examples identified here are not exhaustive. Yet it is apparent that climate change has the potential to alter the release and distribution of environmental contaminants in the environment in a number of ways. The result is a potential change in levels in food and feeds and thence human exposure. The sum of increased and/or decreased emissions and changing distribution patterns depends on the relative significance of the contributing factors. Overall, climate change is likely to increase human exposure to arsenic, cadmium, lead, mercury, dioxins, PAHs and PCBs where food and feeds are contaminated by forest fires, water re-use or increased methylation (mercury only). The situation with respect to BFRs is more uncertain. In addition, there is a potential effect from hazardous waste movement caused by flooding, plus increased uptake due to changed biological systems. The sum of these potential increases may be offset by improved emissions from industrial processes. The overall impact remains to be quantified.

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