



Climate change and food safety: An emerging issue with special focus on Europe

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ABSTRACT

According to general consensus, the global climate is changing, which may also affect agricultural and livestock production. The potential impact of climate change on food security is a widely debated and investigated issue. Nonetheless, the specific impact on safety of food and feed for consumers has remained a less studied topic. This review therefore identifies the various food safety issues that are likely to be affected by changes in climate, particularly in Europe. Amongst the issues identified are mycotoxins formed on plant products in the field or during storage; residues of pesticides in plant products affected by changes in pest pressure; trace elements and/or heavy metals in plant products depending on changes in their abundance and availability in soils; polycyclic aromatic hydrocarbons in foods following changes in long-range atmospheric transport and deposition into the environment; marine biotoxins in seafood following production of phycotoxins by harmful algal blooms; and the presence of pathogenic bacteria in foods following more frequent extreme weather conditions, such as flooding and heat waves. Research topics that are amenable to further research are highlighted.

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1. Introduction

The issue of climate change is increasingly receiving attention from scientists, public, and policy makers. The United Nations (UN) Convention on Climate Change defines climate change as “a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is, in addition to natural climate variability, observed over comparable time periods”. Furthermore, the Convention defines adverse effects of climate change as changes that have deleterious effects on ecosystems, socio-economic systems, and human and animal welfare (United Nations, 1994). One of the main objectives of the Convention is to ascertain that food production

will not be endangered by climate change, indicating the important link between these two items.

The Fourth Report by the UN International Panel on Climate Change (IPCC) was recently published on November 17, 2007 (Bernstein et al., 2007; Solomon et al., 2007). It highlights the general scientific consensus that the global climate has been changing more rapidly in the last years. The report mentions various global climatic changes that are imminent, for example the expected rise in global surface temperatures and sea water levels, and changes in precipitation.

The impact of this climate change on various aspects of human and animal health and welfare is a topic widely debated. However, the consequences of climate change for the food system, which comprises all the stages from “farm to fork” (mainly primary production, processing, transport and trading), have received less attention compared with other human and animal health and welfare issues.

The information that is available in literature mainly focuses on the consequences of climate change on food security, defined by the World Health Organization as access to sufficient, safe and

Abbreviations: DON, deoxynivalenol; EU, European Union; FHB, Fusarium Head Blight; GAP, Good Agricultural Practice; IPCC, International Panel on Climate Change; PAH, polycyclic aromatic hydrocarbon; POP, persistent organic pollutant; UN, United Nations.

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nutritious food. In general, the projected climate change is foreseen to have a negative impact on food security, especially in developing countries. In particular, the abovementioned IPCC report envisages a substantial decline in African crop production due to climate change. In this respect, the Food and Agriculture Organization proactively monitors trends in agricultural production and in factors that affect it, such as transboundary movements of plant pests and livestock diseases, through its GIEWS (Global Information and Early Warning System) and EMPRES (Emergency Prevention System) projects, which make use of satellite technology (ARTEMIS: Advanced Real-Time Environmental Monitoring Information System) and agro-meteorological tools (FAO, 2008a,b).

A relatively new topic is represented by the risks of adverse impacts of climate change on the safety of food. Currently, the issue of vulnerability of food safety to climate change is scarcely considered both at European and at international levels. The issues of food security and food safety are nonetheless related because unacceptable standards of food safety that render food unfit for human consumption will also impair food security, possibly forcing people to consume foods that are of lower quality or contaminated, or that have reduced (bio)availability of certain minerals and/or nutrients. The possible adverse impact of climate change on food safety could therefore also be implicitly included in the UN Convention objectives.

This paper has been produced within the framework of the research on emerging food safety risks that has been carried out by the authors of Work Package 2 of the SAFE FOODS project (<http://www.safefoods.nl>). This project has been sponsored by the European Union's (EU) Sixth Framework Program for Research and Technology Development. The aim of this paper is to describe how the foreseen climate changes can have an impact on food safety, taking into consideration topics that, on the basis of available knowledge, are considered likely to have such an impact on food safety in Europe. The major focus of the paper is on the environmental and agricultural aspects of food production, whilst it does not consider in detail the risks arising from the impact of climate changing on processing, transportation and trading.

It is also taken into account that emerging risks in food in Europe can be the result of climate changes occurring at a worldwide level, due to the globalization of food and feed trade with Europe. This article therefore provides an overview on climate changes projected at worldwide level and subsequently focuses on the European situation. To our knowledge, this article is one of the first papers that consider the possible effects of climate change on food safety by examining a wide range of food safety issues.

This article finally summarizes a number of key findings and provides proposals for future research based on the identified knowledge gaps.

2. Climate change influencing the food system

By means of climate prediction models and scenario studies, scientists attempt to predict the consequence of the observed changes to advice policy makers the best strategy to circumvent the anticipated problems. It is evident that many factors play a role of which much is uncertain, hence a proper overview on the known and the unknown is essential.

Predictions indicate that European and non European areas will encounter rather different effects of the changing climate and consequently its impact on agriculture and food safety will vary for the different geographical regions. These changes, which are explained in more detail below, will have a profound impact on agriculture such as variations in the seasons, alterations in arable land and crop yields, changes in soil quality (such as an increase of losses of soil mineral, variation in their bioavailability and alteration in

soil microorganism ecosystem). Changes are also likely to occur both in number and types of plant pests, as well as in the dissemination of vectors, such as biting insects, and in zoonotic diseases affecting domestic animals and human consumers of plant and animal products. Other aspects of the impact of climate change on food safety include consequences on the livestock production; certain microalgae in seas and oceans; mycotoxins formed by moulds growing on crops; residues of pesticides and persistent contaminants; and pathogenic micro-organisms. These issues are discussed in more detail below.

2.1. General predictions for global climate change

The following climate changes have been identified as relevant for agriculture and food safety: temperature increase, variation in precipitation, drought, and atmospheric carbon dioxide (CO₂).

2.1.1. Temperature increase

According to Solomon and co-workers (2007) the temperature rise foreseen during the 21st century is expected to be highest over land and at high latitudes in the Northern hemisphere during the winter period. The change in temperature is expected to be lowest at the coast and to increase going land inwards. In geographically similar areas, warming is typically larger in arid than in moist regions.

Near-term (by 2050) warming projections are little affected by different scenario assumptions. The highest temperature increase is projected at high Northern latitudes and over land, with less warming over the Southern oceans and North Atlantic (Solomon et al., 2007). In the next 50 years, it is very likely, i.e. with more than 90% probability, that temperatures, averaged over all habitable continents and over many sub-continental land regions, will rise at a greater extent than the global average rate and by an amount substantially in excess of natural variability. It is also very likely that hot extremes and heat waves will continue to become more frequent and long lasting (Bernstein et al., 2007; Solomon et al., 2007). In the mid and high latitudes, almost everywhere a decrease in frost days and an increase in growing season length are projected to occur. According to Solomon and co-workers (2007), "Equilibrium climate sensitivity is likely to be in the range 2–4.5 °C, with a best estimate value of about 3 °C, based upon multiple observational and modeling constraints. It is very unlikely to be less than 1.5 °C." As for the global average surface air warming for the end of the 21st century (2090–2099), the range of *best estimate* and the *likely range* for six Special-Report-on-Emission-Scenarios (SRES) emission marker scenarios are 1.8–4.0 °C and 1.1–2.9 and 2.4–6.4 °C, respectively (Solomon et al., 2007).

2.1.2. Variation in precipitation

According to IPCC (2007), the amount of precipitation is very likely to increase at high latitudes, while in most subtropical land regions (especially at the margins of the subtropic towards the poles) decreases in precipitation are likely, as a consequence of a general intensification of the global hydrological cycle (Solomon et al., 2007). It is very likely that the annual precipitation in European and African regions close to the Mediterranean will greatly decrease as well as the winter rain in South-Western Australia. Extremes of daily precipitation are considered very likely to increase in Northern Europe, Southern and Eastern Asia, Australia, and New Zealand, as well as in many other regions (Solomon et al., 2007).

2.1.3. Drought

The projected tendency for summer drying of the mid-continental areas during summer will imply a greater risk of drought in those regions (Solomon et al., 2007).

2.1.4. Atmospheric CO₂

Atmospheric carbon dioxide (CO₂) concentration has seen a continue increasing from the pre-industrial time and is now almost 100 ppm above. Due to the future global warming the capacity of land and ocean to absorb anthropogenic CO₂ will be reduced. Therefore a higher amount of anthropogenic CO₂ will stay in the atmosphere under a warmer climate (Solomon et al., 2007). In the 21st century, due to the increase of the atmospheric CO₂, the buffer capacity of the marine sea will be altered with the net result of ocean increase acidity; a reduction ranging between 0.14 and 0.35 pH units, in the average pH of global surface ocean, will occur.

2.2. Predictions for climate change in Europe

Recently, in 2007, the European Commission published its green paper on climate change in Europe (European Commission, 2007a). The accompanying annex provides projections of climate change in Europe, as the result of some projects that have produced high resolution maps with the related projected changes in climate variables. The results provided in this report refer to the IPCC scenario whereby no action is taken to reduce greenhouse gas (GHG) emission with a resulting increase in the global mean temperature of approx 3.4 °C by the end of this century. Under this scenario, it is foreseen that up to half of the plant species will be somehow at risk. The main outputs of this annex with respect to variables affecting food and feed safety are reported below, divided by areas and characteristics.

2.2.1. Southern and South-Eastern Europe

This area includes Portugal, Spain, Southern France, Italy, Slovenia, Greece, Malta, Cyprus, Bulgaria, and Southern Romania. For the annual mean temperature, an increase in the order of 4–5 °C is projected in Southern Europe and in the Black Sea region. With regard to water availability, this will be less, with the risk of hydropower disruption, particularly in summer. This effect combined with the rise of temperature could induce (i) decreased agricultural yields (in the range of 10–30% in many regions of the South), (ii) drought, (iii) heat waves, (iv) soil and ecosystem degradation, and (v) eventually desertification. The increase of violent rainfall will augment erosion and loss of organic matter from soil (European Commission, 2007a).

2.2.2. Western and Atlantic Europe

This area includes Benelux, Western and Northern France, Northern Germany, United Kingdom (UK), Ireland, the Netherlands, and Denmark. An annual mean temperature increase in the order of 2.5–3.5 °C (2–3 °C for UK and Ireland) is projected with dryer and hotter summers. Due to higher volumes and intensities of precipitation, particularly in winter, strong storms and floods are projected to be more frequent (European Commission, 2007a).

2.2.3. Central Europe

This area includes Poland, Czech Republic, Slovakia, Hungary, Northern Romania, Southern and Eastern Germany, and Eastern Austria. For the annual mean temperature, an increase in the order of 3–4 °C (4–4.5 °C for Central Europe and Black Sea Regions) is projected. Precipitation is projected to increase in winter and decrease in summer, with an increased risk of floods. Agriculture is expected to be affected by soil erosion, loss of soil organic matter, migration of pests and diseases, summer drought and high temperature. In some regions, longer growing season will benefit crops (European Commission, 2007a).

2.2.4. Northern Europe

This area includes Norway, Sweden, Finland, and Baltic States. An annual mean temperature increase in the order of 3–4.5 °C is

projected. Also an increase of yearly precipitation up to 40% is projected with risks for floods. Winter will be wetter (European Commission, 2007a). For agriculture, the overall results of climate change would be an increase in crop yield (10–30% for warming in the range 1–3 °C) and in cultivated areas. There will also be a possibility for cultivation of new cultivated crops, even though new pests and diseases could appear. In the North European countries, crop production could benefit in terms of aptness and productivity, due to a “lengthened growing season and longer frost-free period. The results, although subject to considerable uncertainties, are consistent with the results of previous studies from the climate change foreseen in those areas” (European Commission, 2007b). Algal bloom and pollution in the Baltic Sea could be more affected by this, potentially leading to food-related problems resulting in concentration of biotoxins in shellfish (European Commission, 2007a).

2.2.5. Marine areas

Due to the projected increase of the average temperature to depths of at least 3000 meters, modifications are projected in overall species composition of the marine ecosystem, therefore affecting fisheries and shellfish sectors. Also the increased acidity of the seas due to the increased absorption of CO₂ will affect the water chemistry of the oceans and thereby, inhibiting calcification, will cause difficulties for marine organisms that build calcareous shells and skeletons (shellfish, corals). The projected rise in water temperature may also have direct and indirect effects on marine organisms, such as on their metabolism and migration to other geographical areas, as well as the formation of harmful algal blooms that could form marine biotoxins and contaminate, for example, mussels used for food production (European Commission, 2007a; EEA, 2007).

2.2.6. River basin and floodplains

The predicted side-effects of floods in Europe that can also be relevant to food safety and production include soil erosion, water pollution, and changes to the ecosystems including aquatic ecosystem with eutrophication and algal bloom (European Commission, 2007a).

2.3. Predicted impact of climate change on agriculture

Climate change will affect agriculture, the degree of possible benefits and drawbacks being strongly dependent mainly on temperature increase, precipitation pattern, and physiological response of crops to enriched CO₂ in the atmosphere. In addition, likely effects of climate change on agriculture include, among others, variations in the seasons, modifications of the areas (e.g. the soil) suitable for growing crops, grazing of livestock, and changes in plant pests.

Climate changes should bring a probable modification of the biogeographical agricultural scenario of cultivated plants: whilst crop yields and the area arable with crops are expected to expand in the Northern parts of Europe, its Southern parts may experience an opposite trend, including decreasing yields, due to increased water deficiency and frequency of episodes of extreme weather, which may render societies vulnerable to the negative impacts of climate change (Maracchi et al., 2005; Olesen and Bindi, 2002; Messerli et al., 2000).

The agricultural system is likely to be the most affected, but also the marine system and the livestock production are likely to be vulnerable.

This section describes the general influence of climate change on agriculture, with the emphasis on arable farming and horticulture, and livestock production.

2.3.1. Arable farming and horticulture

An analysis of the effects of the foreseen climate change on the main sectors of agriculture/farming systems is described here. One should realize that many sectors within agriculture are tightly linked, therefore making the effects due to climate change highly interconnected.

2.3.1.1. Crop systems. Local situations will be affected by the decrease in the amount of yearly precipitation, prolonged dry periods and projected temperature increases that might cause faster growing periods and shorter lifecycles. The timing and length of growing seasons might shift geographically, therefore possibly altering the planting and harvesting dates and likely resulting in the need to change crop varieties currently used in a particular area. Crop systems could also be affected by sea level rise and desertification that cause a decrease in cropping areas.

2.3.1.2. Soil quality. As a projected consequence of climate change in some European areas, the quality of soils will generally deteriorate and in some cases landslides and erosion phenomena due to run off will be occurring (Smith et al., 2005). Increased temperature and altered precipitation patterns might result in increased losses of soil minerals, especially by leaching and erosion. The direction of the net change in plant-available soil minerals is still unclear and large local variations are to be expected (Buol et al., 1990).

Realistic evaluations of the effects of climate change on soil and plant growth are challenged by the complexity and uncertainty of the interrelationships among mineralogy, chemistry, soil microbial populations, rainfall, and temperature (Sparks, 2001). A deeper understanding of such interrelationships would benefit from investigations on soil-forming mineral reactions occurring under diverse climatic and hydrological conditions. Analyses should include detailed characterizations of primary minerals and their weathering products, a census of micro-organisms along with the determination of their patterns of distribution and contextual information about soil physics and chemistry (Loladze, 2002).

In the soil, nutrients and trace elements can be externally or internally bound to various components or be present in the liquid phase, which influences their concentration and speciation in the soil solution and thus their mobility (Kabata-Pendias, 2004). Plant uptake is the result of the interaction of soil-related factors with biological factor. Iron, for instance, is an essential element to plants but is often of limited availability in the soil due to its low solubility and plants have evolved strategies to overcome this problem, such as release of phytosiderophore exudates in the rhizosphere (Hall and Williams, 2003). Microorganisms play a pivotal role in trace element uptake as well. They react to high or low element concentrations in soil in a variety of ways. One biochemical response to toxic levels of trace elements is the production of extra-cellular polymers that bind and effectively immobilize the element-containing compounds and, in some cases, biomineralization (Banfield et al., 1999). For example, microbes immobilize uranium (U) by intra- and extra-cellular precipitation of secondary minerals. Alternatively, some microbes exposed to arsenic (As) utilize mobile genetic structures (plasmids) to synthesize proteins that reduce the less toxic As^{5+} to more toxic As^{3+} and secrete it from their cells (Silver, 1997). In other cases, microbes can volatilize toxic elements (e.g. mercury by formation of methyl-mercury compounds). Micro-organisms also affect the distribution and bio-availability of essential elements. Thus, microbial responses to elements can dramatically change elemental speciation and accessibility in soil.

2.3.1.3. Crop yields. Crop yields are expected to change across European countries. Southern Europe will probably experience

decreases for spring-sown crops such as maize, sunflowers, and soybean; the same becoming more suitable than previously for cultivation in Northern areas. Maize production is expected to increase by 30–50% in Northern European regions but to decrease strongly in the South of Europe (Wolf and Menne, 2007).

Changes in yield level, all other factors being equal, will imply a corresponding adjustment of fertilizer inputs (Sinclair, 1992). Fertilizer use is adjusted to fit both the uptake of nutrients by crops and any losses of nutrients that may occur during or between growing seasons. Predictable increases in atmospheric CO_2 concentration will cause a higher nitrogen uptake by crops and thus larger fertilizer applications. On the other hand, climatic constraints on yields may lead to a lower demand for fertilizers depending on local pedology. Climate changes may also influence nitrogen losses through leaching or volatilization in an unpredictable manner. All together these factors may lead to changes in the demand for fertilizer and possibly greater risks related to the exploitation of sources and raw materials with higher trace element impurities due to increased consumption.

The type of fertilizers will be largely determined, inter alia, by the dynamics of moisture availability. In dry conditions, the water contained in a liquid sludge enables nutrients to reach the crop rooting zone more effectively than in the case of a synthetic fertilizer. It has been noted that the levels of some minerals such as phosphorus, calcium, and iron are higher in crops fertilized with sludge.

Current fertilizer practices are based to some extent on models and mainly on empirical functions obtained in field experiments. These models and functions are updated regularly on the basis of new experimental evidence. This process will probably capture the response of changes in the environment through CO_2 and climate.

It is important, however, that agricultural researchers and advisors are aware of the possible impact of global change on the use of external inputs, so that older empirical data are used with proper caution.

2.3.1.4. Crop associated biological environment. According to Rosenzweig and co-workers (2001), higher temperatures and a greater incidence and intensity of extreme weather may lead not only to significant modifications in crop systems and yield, but also to an expanding range of crop pests and altered transmission dynamics of insects, pests, and plant diseases, which will exacerbate the yield reduction and impair food safety if appropriate measures are not taken in due time. As for the changes in crop insects, weeds, and diseases, these authors especially address the fact that a change in patterns of precipitation may be even more important for crop pests' interactions than a change in annual total precipitation. Projected temperature increases can be expected to cause increased pest damage at the sensitive earlier stage of crop development. The disproportionate warming at high altitudes and high elevation in winter and nighttime can affect not only crop development, but also alter the ecological balance between the crop and its associated pests.

In particular climate changes could impact the ability of insects to overwinter, the geographic distribution or ranges of insects, and the number of generations and their abundance in agricultural systems. Petzoldt and Seaman (2005) conclude that the precise impact of climate change on insects and pathogens is somewhat uncertain because some climate changes may favor, while others may inhibit a few insects and pathogens. The preponderance of evidence indicates that there will be an overall increase in the number of outbreaks of a wider variety of insects and pathogens.

Climate change will probably increase the spread of both the existing and emerging pests; whenever climatic change can influence the interaction between insects and agricultural plants, each

case should be analyzed individually, depending on the insects and plant under consideration. As an example, a study of possible consequences of climate change on potential sources of new invasive insect pests in the Gisborne District in New Zealand is mentioned here. Altered wind patterns could affect the long distance movements of some species: analyses with climatic data showed that the time of the year when most species start to fly shifts to earlier dates with increasing winter temperature (Rosenzweig et al., 2002).

2.3.2. Livestock production

The potential impact of climate change on livestock does not have the same public recognition as the impact on crop systems, but, also in this respect, both harmful and beneficial effects of climate change could be hypothesized, depending on the area and circumstances.

Animals can cope with the changing meteorological parameters more easily than crops because of their mobility and ability to adapt to different surroundings and to different feed (Anonymous, 1997). For example, technical adaptation, such as ventilation and cooling systems, can be easily, even though costly, installed in stables to face temperature rise.

The effects of climate change on livestock can be direct, such as the link of stress factors (e.g. high temperature) on livestock appetite. An indirect influence of climate changes can be seen in the requested modification of the quantity and moreover on the quality of forages from grasslands and the supplies of concentrates; this key factor highlighted during the third assessment report (Watson et al., 2001), was also included as “new knowledge” in the fourth assessment report (Bernstein et al., 2007) in view of recent studies that contributed with specific new knowledge with respect to several uncertainties and limiting factors.

Positive effects of climate changes, such as increased temperature and sufficient moisture, pose beneficial consequences for production efficiencies of yields in the affected areas.

As for the necessary water resources, a response to climate change would include the upgrading of the related establishments, including technical devices that are essential for the quality and reprocessing of water in order to guarantee the survival (Anonymous, 1997) and the preservation of animal health.

The increasing temperature as an effect of climate change could imply the potential of increase in animal diseases due to the shift of pathogens to more favorable host environments (e.g. multiplication of pathogens in animal feed). In addition, environmental changes can cause movements of animals, which act as vectors for the mentioned pathogens (Klinedinst et al., 1993).

Production efficiency of livestock can also be affected by changes of temperature. Estimates of livestock production suggest negative effects of heat waves during summertime, but this could be balanced by the positive effects of warmer winters (Adams et al., 1999). Furthermore, warmer winter times imply a non-negligible economic advantage attributable to the reduction of the cold stress on livestock and of the energy requirements for the heating devices of animal facilities (Anonymous, 1997).

Many of the items discussed above should result in modifications of the Good Agricultural Practice (GAP) and Good Farming Practice. Not always will the involved stakeholders (i.e. manufacturers, farmers) be aware or prone to the necessary adaptations of the existing protocols, and this will negatively affect both yield and safety of the produced food and feed.

2.4. Models on climate change and agriculture

The issue of climate change and food has been addressed in many studies since the nineties (Parry et al., 1995; Rosenzweig et al., 2001; Watson et al., 2001; National Research Council,

2001). Most of these studies use (integrated) climate models and scenarios. These models often embody a number of simplifications. For example, weeds, diseases, and insect pests are assumed to be controlled; there are no problems in relation to soil conditions (e.g. salinity or acidity); and there are no extreme weather events. The absolute effects of climatic change on the local yields may be different from the simulated ones (Rosenzweig et al., 1993). Although global climate models have improved over time, they still have limitations that affect the simulation of extreme events (Bernstein et al., 2007).

Besides the (integrated) climate models (e.g. IMAGE; MNP, 2008), also more specific models have been developed that model species response to climate (e.g. Climex model; CSIRO, 2008). With the help of such models the distribution of insects, plants, pathogens, and vertebrates can be examined for a variety of purposes (invasive species risk analysis, vector-borne diseases, vulnerability to pests).

An evaluation of the status of the art of the proposed models leads to the following preliminary conclusions:

- Most (integrated) climate models have difficulties to address the impact on pests and diseases;
- Models exist that examine the distribution of insects, plants, pathogens under climate change;
- It is important to address warming trends and changes in extreme;
- Changes in pattern of precipitation may be more important than annual totals;
- The occurrence of pests and diseases have a local and regional dimension;
- Not much is known about the responses of insects and plant diseases to warming;
- Quantification of the impact of climate change on pests and diseases is lacking.

For further research on climate change and food safety, it is relevant to take notice of these conclusions. Although (integrated) climate models and scenarios may lack specific details, they can serve as a common framework for impact studies.

3. Assessment of the vulnerability of the food safety systems to climate change

3.1. General issues

To deal with emerging food safety risks caused by climate change, a large variety of disciplines are needed ranging from natural to social science and, as a consequence, a holistic approach is advisable to adequately tackle the complexity encountered.

Typically the impact assessment on different aspects of human health, including the safety of our food, refers as maximum to 20 years, therefore allowing the use of an array of methodologies “at near or mid period”. The impact assessment of the vulnerability of the food safety systems to climate change implies as a minimum up to 50 years time scale, therefore needing impact assessment based on scenario formulation. In this last respect, impact assessment under transient scenario is preferred.

An important issue is “how much likely” climate change will have an impact on each of the specific topics related to food safety. In other words, when assessing the specific emerging risks, an issue is to discern among “speculative” and “knowledge-based” risks, also in view of assigning priority to adaptation measures. Qualitative or quantitative correlations with climate (change) indicators have been reported for many food safety issues. In some cases, correlations are supported by experimental data, while some

of them are not based on validated models, or are given as hypothesis, even though on an extremely reasonable basis.

These uncertainties should be added to those of the expected climate change, as treated by Solomon and co-workers (2007), thereby enhancing the overall uncertainty of the assessment of the vulnerability of food safety to climate change.

A step-by-step approach for the impact assessment implies (i) the qualitative identification of climate-related determinants of the vulnerability for each topic; (ii) the evaluation of the degree of knowledge on the correlation between each topic and one or more climatic determinants; and (iii) the comprehensive analysis linking the identified determinants of predicted climate change with each topic on a regional basis.

In this respect, an emblematic case is represented by mycotoxins, for which knowledge-based quantitative correlations with temperature, humidity, and insect attack pattern are available, whilst correlations with wind- and climate-related characteristic of the soil have been hypothesized, but not quantitatively nor semi-quantitatively stated. Similarly, each climate-related topic of food safety has its own pattern of “knowledge based” and “speculative” previsions.

Likewise, the prediction of – and warning systems for – the occurrence of harmful algal blooms, which may be prone to phyco-toxin production and contamination of shellfish, are in a well-developed state. Also the recently observed movement of zoonotic agents caused by altered dissemination of their vectors, such as bluetongue by midges, may also provide a useful resource of data.

In order to prioritize adaptation measure, also an evaluation of the societal health concerns linked to the food safety risks induced by climate change is needed. In this respect, the analysis should be based both on the severity of the hazard and on the likely of the risk.

The focus of this article does not include mitigation/adaptation measures to be adopted as response to the impact of climate changing on food safety, although some consideration is devoted to this topic. However, emphasis should be given to the fact that development and employment of genetically modified (GM) crop plants could alleviate many of the concerns about potential impacts of climate change on agriculture, such as a potential rise in soil salinity in coastal areas and dryness in subtropics.

3.2. Topics of interest

Considering the abovementioned issues, we propose the following subjects of pivotal interest in the field of food safety as topics for further research. The topics were selected by the authors on the basis of the existing knowledge on these topics, their probable sensitivity to the foreseen climate changes, and the severity of their impact on human and animal health.

3.2.1. Mycotoxins

Despite efforts to control contamination by moulds, toxigenic moulds are ubiquitous in nature and occur regularly in worldwide food supplies due to mould infestation of susceptible agricultural products, such as cereal grains, nuts, and fruits (Murphy et al., 2006).

Mycotoxins, produced as metabolites of toxigenic moulds, exert a severe adverse effect on human and animal health due to their recognized toxic properties, which depend on the particular mycotoxin and on its dose. Well ascertained characteristics include genotoxicity for aflatoxin B₁; carcinogenicity for aflatoxins, ochratoxin A, and fumonisins; and immunotoxicity for a number of mycotoxins.

A wide body of evidence demonstrates that the ability of moulds to produce mycotoxins is greatly influenced by environmental factors, mainly temperature, relative humidity, insect

attack, drought, and stress condition of the plants. Furthermore, a study by Simpson and co-workers in 2004 revealed that the pathogenicity of different varieties of moulds may be partially additive, and that the selective advantage of one over another may be temperature-dependent (Simpson et al., 2004). In this section, relevant findings on the correlations between climate and fungi contamination/mycotoxin production are summarized with a special focus on fungi affecting cereals that are commonly consumed in Europe.

In wheat, the species profile of Fusarium Head Blight (FHB) in different geographic areas depends on several factors, primarily climatic conditions, particularly temperature. Weather conditions influence different parts of the infection cycle: intense rainfall during the period of anthesis can effectively disperse *Fusarium* inocula to ears; prolonged period of warm humid conditions are conducive to infection of cereal ears by *Fusarium* spp (Jenkinson and Parry, 1994; Parry et al., 1995). Among *Fusarium* species associated with FHB, *Fusarium graminearum*, the main deoxynivalenol (DON) producer, is favored by the warmer climate of Southern Europe. However, there are still insufficient quantitative data to draw any firm conclusions on the impact of environmental parameters on FHB development caused by individual – and combinations of – mould species (Xu, 2003). Grain harvested from *Fusarium*-infected ears is frequently of poorer quality and contaminated with mycotoxins, including the highly toxic trichothecene mycotoxins, such as DON. Cycling of temperature can also have a significant impact on DON production (Hope et al., 2005).

The *Fusarium* mycotoxin (DON, nivalenol, and zearalenone) content of wheat crops depends on both year and cropping system including the use of fertilizers, which in turn can be driven by climatic changes (Champeil et al., 2004). Fertilizer regimes may affect FHB incidence and severity either by (i) altering the rate of residue decomposition, (ii) creating a physiological stress on the host plant, or (iii) altering the crop canopy structure (Edwards, 2004). For example, higher nitrogen (N) inputs extend the stages during which wheat is susceptible to infection, a longer flowering period and later ripening. The risk of nitrate leaching in crop fertilized with mineral or organic N is weather- and soil-dependent. To understand the impacts of yearly weather variations, long-term climate, soils, and management on nitrate-N leaching, long-term field experiments in different regions and on different soils will be necessary.

Maize can support different mycotoxin-producing moulds, such as *F. graminearum*, *Fusarium verticillioides*, and *Aspergillus flavus*, and the dominant species is determined by meteorological conditions. In 2003, prolonged hot and dry weather caused an outbreak of *A. flavus*, the most xerophilic of the cited moulds, with consequent problems of aflatoxins contamination that had previously been uncommon in Europe, Southern areas included. Aflatoxins, produced by few species belonging to *Aspergillus* section *Flavi*, are specifically expected to become more prevalent with the foreseen climate change (Bunyavanich et al., 2003).

F. verticillioides, a producer of the fumonisin toxins, is the most common species on maize in Southern Europe. Fumonisins have been associated with both dry weather during grain fill and late-season rains (Munkvold and Desjardins, 1997); therefore the production of the toxins will be favored by the foreseen climate change.

Mild temperature and rain during maize plant growth is conducive to plant infection by *F. graminearum*. The problem is relevant in several growing areas in central Europe, whilst significant DON levels were detected in Italy for the last time in 1995.

Furthermore, mould distribution and cycle are largely influenced by insect attack on plants, thereby establishing a correlation with the already described impact of climate change on insects.

The information summarized above suggests that the effect of climate change on the colonization by moulds and production of

mycotoxins should be evaluated on a case-by-case basis since every mould species has its own optimum conditions of temperature and water activity for growth and formation of toxic metabolites.

Another effect of climate change may be the diminished productivity of crops that are used for producing food and feed, either as a result of the conversion of arable land to biofuel production in order to cut the balance of greenhouse gas emission, or as the abovementioned result of diminished crop yields due to climatic conditions. As a consequence, shortages in crop resources may have to be compensated with different crops or the same crop of a lower quality grade, potentially containing mycotoxins of a different nature or with higher prevalence. Both the changes in weather conditions and the modifications of the biogeographical scenarios of crop cultivation could trigger the adoption of new GAPs targeted to face mould infestations and mycotoxin contaminations.

The main research needs aimed at assessing the impact of climate change on mycotoxin contamination and the related adaptation measures are herein briefly outlined, as follows:

- Harmonization of procedures for the surveillance and monitoring of mycotoxins across Europe;
- Evaluating the feasibility of a reliable database on the geographical distribution of mycotoxins and on the prevention methodologies used across Europe during the last decades;
- Development of models for the prediction of the novel biogeographical agricultural scenarios of cultivated plants and of the related moulds/mycotoxins;
- Evaluation of the influence of multiple environmental factors on mycotoxin contamination.

3.2.2. Pesticides

Climatic changes across the globe will influence agricultural systems. Due to among others changes in mean and extreme temperatures and rainfall patterns, there will be a change in crops grown in the different zones of cultivation. Not only this change but also the expected increase in the prevalence of plant pests and diseases, as well as weeds, will have an effect on the use of pesticides. Moreover, climate change may affect the pesticidal activity of some pesticides. According to Bloomfield et al. (2006), long-term land-use change driven by changes in climate may have a more significant effect on pesticides in the environment than the direct impacts of climate change on specific pesticide fate and transport processes. According to Hall and co-workers (2002) and Rosenzweig and co-workers (2001), the changing weather patterns will lead to an increase in pest outbreaks in crops and therefore an increase in the use of agrochemicals. It is anticipated that such practice will result in a higher risk of elevated exposures of humans to pesticides via residues in their food. The ultimate result of these changes may be an alteration in pesticide use resulting in a change in type of residues, residue levels, and residue occurrence in food commodities.

The expected decrease of soil organic matter with temperature increase may result in an increased root uptake of pesticides that are otherwise bound to organic matter, or depending on the physicochemical characteristics of the pesticide, to larger evaporation rates. Furthermore, 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). In an investigation of the relationship between pesticide usage and climate change in the United States, Chen and McCarl (2001) concluded that an increase in precipitation rates results in an increase in pesticide

usage costs in the crops they investigated, as does an increase in temperature in most but not all investigated crops.

The general conclusion is that in future due attention should be given to the influence of changing climate conditions on the use of pesticides according to GAP, as current GAP may not be suitable to the future status of crops.

In addition, although many nations are obliged to have monitoring in place for pesticide residues, monitoring results of the different nations may not be comparable due to, among others, differences in analytical methods used. Furthermore, due to the authorizations of pesticides at the national level, insight at the international level of currently authorized uses in the different nations is missing. This is also true for information on actual use levels in different crops in the different nations. In order to assess the effect of changes in pesticide use due to climate change on food safety it is essential:

- To further harmonize monitoring for pesticide residues in the different nations;
- To monitor at the international level, such as the EU level, the authorizations given to the use of pesticides in the different nations, and changes therein;
- To explore methodologies for deriving actual pesticide usage data;
- To develop and integrate models for the prediction of changes in crops, cropping systems and plant pests, and pesticide usage.

3.2.3. Trace elements

The potential effects of climate change on the transfer of trace elements within the soil–plant chain can be divided in two main groups, i.e. effects on plant development and resistance, and risks for human health, which are further explained below.

3.2.3.1. Effects on plant development and resistance. Depending on the geographic area, foreseen climatic changes may alter soil conditions and element availability so severely to overwhelm the tolerance and adaptation of certain plant species to new or chemically imbalanced growth media. For instance, interactive effects of temperature and heavy metal stress on wheat have been reported (Öncel et al., 2000). Deficiency of nutrients or excess of toxic elements may result in a lower resistance to insects, pests, and plant diseases. In turn, this would determine decreasing yields and changes in the demand for fertilizers and other chemicals.

Increased use of chemicals is unfavorable; furthermore, it may adversely affect the uptake of toxic trace elements, as shown for cadmium (Cd) following application of phosphate fertilizers (Grant et al., 2002).

3.2.3.2. Risks for human health. A first risk is represented by the possible build-up of potentially toxic trace elements in certain plants and other agricultural products due to variation in pedoclimatic conditions. Arsenic (As) in its inorganic forms, cadmium (Cd), lead (Pb), and mercury (Hg) are of major concern. The former three elements represent actual hazards in terrestrial environment, whilst Hg is of concern mainly in the aquatic ecosystem. However, several other trace elements are relevant in this context as well.

Moreover, any change that would affect the safety of produce in terms of element content could have repercussions on human health either directly or following the use of plant products as feed for growing livestock.

A second risk is represented by a shortage of essential microelements in the food supply due to decreased concentrations in the produce. Essential elements for which the risk of deficiency in humans is the greatest include iron (Fe), zinc (Zn) and selenium (Se). A recent study highlighted the importance of pedoclimatic

variables related to fluctuations of soil moisture and pH (e.g. temperature and rain intensity excursions) in determining the concentration of Se in wheat grain (Spadoni et al., 2007). A multiple regression model based on six geochemical and pedoclimatic variables was developed and used to predict selenium concentration in grain with an acceptable level of agreement with biogeochemical maps based on measured Se in wheat.

For some elements, such as As and Se, the identification of the chemical form(s) (species) present in food is of crucial importance as this form critically influences their availability and biological effects in humans (Cubadda, 2004). Therefore, for such elements, the selective study of the bioactive species of trace elements (speciation) is necessary in order to gain relevant information for risk assessment.

3.2.3.3. Research. It is presently unclear what the relative importance of the two groups of effects outlined above (i.e. effects on plant produce and risks for human health) will be in terms of increased climate-related risk, even though evidence already exists that subtle changes of climatic variables can significantly affect the development and resistance of certain plant crops. For both groups of effects, research should focus on the identification of the most vulnerable plant species in the various geographic areas. Field studies under controlled conditions should be carried out to investigate changes in the concentration of a number of relevant elements (multi-element profiles) and stable isotope ratios (e.g. nitrogen) in plants. Information at the molecular level (speciation analysis) would be required for some elements in order to assess potential health effects on humans. Genetic variability (plant cultivar) is a factor influencing element concentrations in some cases, as demonstrated for Cd in durum wheat grain (Penner et al., 1995), and has to be considered as a relevant variable in such studies. On the basis of the data obtained in the case studies outlined above, models should be developed to provide estimation of impact (primarily as change in multi-element profiles) in response to changes in climate variables. The final outcome should be the development of predictive models which help in identifying changes in the type of produce and soil management required at regional level to tackle climate change.

3.2.4. Polycyclic aromatic hydrocarbons (PAHs)

The PAHs are environmental contaminants recognized as carcinogenic and mutagenic agents (Bostrom et al., 2002). Their presence in air, dust, soil, water, and food is of concern for human health because of possible adverse effects following exposure by air inhalation, food ingestion, water drinking, and accidental ingestion of contaminated dust or soil.

Climate changes have the capability of affecting the PAH distribution and fate in the different environmental compartments (i.e., air, dust, soil, water). In fact, PAHs are known to undergo Long Range Atmospheric Transport, moving according to their physico-chemical characteristics and to the type of the surroundings that they come across. Although PAHs are locally released, they can be, in particular circumstances, transported over very long distances. This phenomenon can occur as a single “jump” (emission-transport-deposition) or by multiple “jumps” (deposition onto a surface and further emission; Wania and Mackay, 1996). The number of “jumps” and, consequently, the transport distance depend on climatic conditions, on the type of surface (dust, soil, water, vegetation, etc.) and on the physico-chemical properties of a given PAH.

According to these last, PAHs with higher volatility will be subject to multiple “jumps” with final deposition in pristine areas, while those with lower volatility will accumulate preferably in areas closer to the first emission source (Bouchard et al., 2001).

A key factor able to influence the worldwide distribution of PAHs is undoubtedly the temperature. This last directly influences phenomena such as emission degree from pollution sources, gas-particle partitioning of PAHs in atmosphere, bio- and chemical-degradation rates, and air-surface exchange. A temperature increase can, for example, enhance secondary emission phenomena (re-volatilization of PAHs from areas previously contaminated).

Other climate-related variables such as wind and frequency and intensity of the atmospheric events can also influence the atmospheric transport of PAHs and the behavior of these compounds in the environment. An increase of rains can, for example, cause a spread of PAHs deposition onto the soil and, at the same time, may enhance the mobilization of PAHs stored in the soil compartment. The mobilized PAHs can be transferred by land runoffs to the superficial waters making them bio-available to the aquatic organisms.

It has already been proven that the changes in both temperature and wind are associated with atmospheric circulation outlines (Pauluis et al., 2008; Wallace and Gutzler, 1981). In particular, the escalation in the frequency and intensity of heat waves over Europe has been correlated with an enhanced persistence of the atmospheric circulation (Kysely, 2007). A recent study has underlined the potential influence of climate changes associated with atmospheric circulation patterns on the distribution, both spatial and temporal, of persistent organic pollutants (POPs; Jianmin et al., 2004). In like manner, atmospheric concentration of PAHs and their fate could be influenced by a more persistent air circulation over the European latitudes.

The distribution of PAHs among the environmental compartments is also determined by the capacity of the exchange surfaces (soil, water, vegetation) to hold, to accumulate or to degrade them. As regards this last aspect, it is opportune to remember that PAHs can be decomposed by photolysis and via radical-mediated reactions, both depending on the ultraviolet (UV) ray intensity (Niu et al., 2004; Mandalakis et al., 2003).

Thus, the capability of an environmental compartment to retain and/or release PAHs, depending on many parameters, is widely variable according to short- and long-term trends (Dimashki et al., 2001; Halsall et al., 1997; Lee and Jones, 1999; Ohura et al., 2004; Sepic et al., 1997).

The results of possible climatic changes, which can have repercussions, for example, on the increase of desertification phenomena, changes in soil property and in land use, the glacier retreat, and the change of autochthonous flora can therefore considerably affect the worldwide fate and distribution of PAHs (Macdonald et al., 2005).

A different distribution of PAHs in air, soil, and water provides a spin-off for food safety, giving rise to a different degree of contamination for foods of animal and vegetable origin. It is therefore important, especially at the regional scale, to take fully into account all the possible climatic variations when trying to predict the future environmental pollution of PAHs and, consequently, the food contamination. Interestingly, the Institute of Environment and Sustainability investigates, among others, the effect of climate change on the mobilization of atmospheric POPs and their deposition in water bodies as part of its support to the implementation of EU legislation on water and environmental quality (JRC, 2005).

After the approval of international agreements such as the Aarhus protocol and the Stockholm Convention, PAH emissions are decreasing in developed countries, although, in the last years, there have not been further improvements. This overall decrease has been achieved through technological progress and legislation besides a decreased use of coal and coal products. This notwithstanding, the PAHs are still and probably will be cause of concern for the following reasons:

- Emissions from some combustion sources, especially from wood combustion (the largest source of atmospheric PAHs), have not shown a significant decrease (Holland et al., 2001);
- Only few countries have monitoring networks;
- Emission inventories for PAHs have a high uncertainty (<50 %) and different protocols are used in the world to collect and analyze environmental PAHs (poor inter-comparability);
- Countries undergoing rapid industrialization (i.e. China, India, Brazil) are increasing the PAH emissions in global terms since mobile, domestic, and industrial sources continue to grow at a high rate.

For the reasons mentioned above, further studies have to be encouraged in the next years:

- To assess the transfer mechanisms of PAHs from the different sources to environmental compartments and food chain;
- To develop and validate analytical methods for the detection and determination of PAHs in environmental and food matrices;
- To track the distribution of some selected PAHs in foods, focusing on the influence of climate change by considering different climate scenarios;
- To verify if even relatively modest climate and environmental changes can trigger a much more significant variation in fate and distribution of PAHs by applying reliable predictive models.

3.2.5. Marine biotoxins (phycotoxins)

Certain microalgae in seas and oceans, including dinoflagellates and diatoms, can form extensive monocultures. The conditions favoring this growth include water temperature, sunlight, competing micro-organisms, nutrients (phosphorus, nitrogen, microelements), wind and directions of currents. This growth therefore not only depends on water temperature, but also on other factors, such as eutrophication by pollution of water with nutrients originating from human activities.

A number of these algae produce toxic compounds of a widely varying nature, such as polyethers or cyclic polypeptides. These toxins not only exert adverse effects on other marine organisms, but also on human consumers of seafood containing these toxins or beach dwellers inhaling seawater aerosols. For example, water-filtrating organisms, such as mussels and clams, are prone to contamination with these toxins; their own resistance may relate to a mutation in a neural protein. The symptoms that these toxins may cause after consumption are, for example, Paralytic Shellfish Poisoning (PSP) and Diarrhetic Shellfish Poisoning (DSP). The abovementioned monocultures that are caused by bursts in algal growth have been dubbed “red tides” due to the pigment of some of the algae involved, and more generally as “harmful algal blooms.” Besides toxin production, the red tides may also cause a decrease in oxygen levels, resulting in anoxia or hypoxia with detrimental consequences for sea life. Governments have warning systems in place that monitor for harmful algal blooms, which are instrumental in risk management, such as in delays of shellfish harvests to allow for “wash-out” of toxins, if needed.

A perceived increase of harmful algal blooms has been globally registered with important ecological and economic consequences due to their effects on coastal marine resources. Even if these events seem mainly due to various aspects (such as tourism expansion, economic exchanges, eutrophication; e.g. Anderson et al., 2002), some authors have stressed that climate variability is equally important (Sellner et al., 2003). It was observed that climate change has direct physiological effects through enhanced growth and reproduction of some dinoflagellates and indirectly modifying the environment, by the increase of the temperature or by the precipitation producing a general decrease of the salinity.

Consequently the effects on dinoflagellates could be an increase in blooms of certain genera (e.g. *Prorocentrum*, *Ceratium*, *Dinophysis*, etc.), leading to an increase in toxic and anoxic events in some areas.

In the last decades, various dinoflagellates have been found in the sea of different European Countries, including some marine dinoflagellates, such as *Alexandrium ostenfeldii*, producing spirolides that are a kind of marine toxins belonging to the cyclic imines group. Also benthic dinoflagellates have been found that belong to the genera *Ostreopsis*, producing palytoxin and usually living in tropical and subtropical areas (Villar Gonzales et al., 2006; John et al., 2003; Monti et al., 2007). These occurrences of dinoflagellates can lead to health risks and economical losses as a consequence. Retrospective analysis of algal blooms in the North Sea shows that some areas, such as the Norwegian coast, are more vulnerable than others to increased algal blooms (Edwards et al., 2006). Projections of future algal blooms in the North Sea indicate that their growth periods may become more extended, which, in turn, may have implications for the harvest of shellfish (Peperzak, 2003).

Interestingly, a recent article that studied climatological and food poisoning data from French Polynesia reported that human intoxication by consumption of fish containing the algal ciguatera toxin occurs approximately 19 months after increased temperatures occur (Chateau Degat et al., 2005). Similar to the marine harmful algal blooms, the same reasoning also applies to cyanobacterial blooms in freshwater reserves during warm periods. It should be cautioned, though, that for each algal species associated with human illness, there exist specific environmental conditions that cannot be generalized. Strategies and approaches for preventing or mitigating climate change stresses and controlling their effects on coastal marine resources should be based on the capacity to anticipate changes with sufficient lead-time and to make decisions (Clark et al., 2001).

For both implementing adaptive managements and assessing their efficacy, studies have to be encouraged for:

- Increasing the monitoring of water quality and harmful algal blooms;
- Improving and validating toxin detection methods;
- Determining the relation between quantitative occurrence of toxin-producing microalgae (planktonic and epiphytic) and the accumulation of biotoxins in bivalve molluscs;
- Clarifying the mechanism of action for a number of toxin groups;
- Generating more toxicological data to allow more accurate risk assessment to elaborate recommendations;
- Information on bloom species selection, species interactions (e.g. after invasions of exotic species with ballast water) and interactions of blooms with climate factors;
- Development of operational models for forecasting blooms of toxin-producing microalgae in time and space, in relation to climate change (considering not only temperature but also other parameters, such as irradiation, precipitation, currents, etc.).

3.2.6. Food and feed micro-organisms

Climate change has been identified as having potential for increasing bacterial contamination of food and water, which consequently may result in a change of risks related to water- and food-borne infection diseases (Rose et al., 2001). Water- and food-borne bacteria can cause mild to serious human gastrointestinal disease and in part severe complicating problems such as hemorrhagic colitis or hemolytic-uremic syndrome (*Escherichia coli* O157:H7), Guillain-Barré syndrome (*Campylobacter* spp.) and meningitis (*Listeria monocytogenes*). Although it is possible to establish

correlations between meteorological parameters and the behavior of bacterial food pathogens in some cases, it is at present not yet possible to fully predict water- and food-borne bacteriosis caused by climate changes. Moreover, this is compounded by incomplete data on the epidemiology of many infectious diseases. Nonetheless, it is important to explore the potential changes in disease patterns under the conditions of global climate change (McMichael et al., 2003).

The problem of bacterial pathogens is complicated by the fact that many of these organisms can survive for long periods and multiply in the environment. For example, the pathogenic water- and food-borne bacteria *E. coli* O157:H7, *L. monocytogenes*, *Salmonella* spp. and *Campylobacter* spp. are able to persist for extended periods in the environment (McGee et al., 2002; Müller, 1996; LeJeune et al., 2001). Survival, multiplication, or transmission potential of bacteria in the environment, food, and feed are especially influenced by temperature, rainfall, flooding and humidity, but other factors such as wind can also be significant. Furthermore, many bacterial pathogens found in food are ubiquitous, particularly on farms and in aquatic environments (Isaacson et al., 2004). The survival of pathogens in the environment is important for the possible transmission of bacteria leading to contamination of food and water.

Most of the viruses, bacteria, and protozoa that cause water- and food-borne diseases thrive in warm water and weather. Therefore, increased water and air temperatures could stimulate the increase of the circulation of harmful pathogens. For example, it is known that weather influences the survival through factors such as temperature, and the dissemination of pathogenic agents, including viruses, through rainfall and runoff. This contaminated runoff will either be discharged directly into water bodies or pass down through the soil and contaminate groundwater and drinking water wells. Then changes in precipitation, temperature, humidity, salinity, and wind have an important effect on water quality and may consequently raise the risk of contamination events (Gantzer et al., 1998; Wetz et al., 2004).

The existence of seasonal fluctuations of water- and food-borne pathogens in the environment and the incidence of animals and human diseases are based, among other things, on meteorological factors (e.g. temperature or precipitation), whereas the seasonal relationships vary from pathogen to pathogen. Several studies have indicated a strong relationship between the incidence of food-borne disease and temperature in the month preceding the illness. For many bacterial or viral diseases, there is a clear seasonal trend in the detection or isolation of a pathogen and prevalence of disease. For example, the water-borne pathogen *Vibrio vulnificus* is strongly influenced by weather parameters, especially temperature, which dictate its seasonality distribution (Lipp and Rose, 1997). In several studies, a seasonality of *Salmonella* spp. in dairy cows (Pangloli et al., 2008) or gilt (Vonnahme et al., 2007), and of *E. coli* O157:H7 in cattle (Elder et al., 2000), depending on meteorological parameters, could be noted.

Particularly for viral infections, the water–food connection is important. It is known that fish and shellfish from contaminated water have worldwide been major sources of viral diseases. Moreover, there have been instances of viral diseases associated with consumption of fresh fruits and vegetables due to the viral contamination via irrigation waters (Tauxe, 1997).

Analyses of epidemiological data indicate for certain pathogens a relationship with extreme weather events. A number of recent studies examined extreme precipitation events. In these studies, it was concluded that an increase in frequency and severity of extreme precipitation events related to climate change would result in an increase in the risk of contamination events, for example the discharge of contaminants into waterways, which would eventually increase the risk of water- and food-borne illnesses (Curriero et al.,

2001; Rose et al., 2001; Kistemann et al., 2002). A good example of a possible countermeasure is the implementation of new drinking water regulations in England and Wales in 2000, which effected a significantly reduction of cryptosporidiosis cases (Lake et al., 2007).

The food chain (production, transport, sale, and household) may also be affected by climate change on the basis of changing survival or multiplication of some food-borne pathogens. For example, multiplication of *Salmonella* spp., an important source of food poisoning, is strongly temperature-dependent. An increase in temperature or in duration of high-temperature episodes in particular geographical areas may allow better conditions for multiplication of *Salmonella* spp. in foods. The replication of food-borne viruses will not be promoted by an increase of temperature, though, because they are not able to replicate outside an animal or human host. Regarding the storage of foods, the maintenance of the cold chain throughout the whole food chain is important, as is the consumer's understanding of appropriate food handling. This could be achieved by general information for the public and training measures for consumers.

According to McMichael and co-workers (2003), the recommended further research could be focused on three questions to evaluate the possible extent of changing pattern of infectious diseases as a result of changing climatic conditions:

1. Can recent data be used to evaluate the climate impact on the prevalence of infectious diseases?
2. Has the prevalence of infectious diseases changed due to climate change during the last decades?
3. Is it possible – with the help of existing expertise and reflections – to integrate different predictive models to assess how different parameters of climate will influence the transmissibility of particular infectious diseases?

For answering these questions, detailed incidence data across several populations and geographical areas in Europe will be required as basis for epidemiological studies, whereas preferably from the beginning of the evaluation of data, meteorological relationships with these incidences should be considered. In this context, also long-term climate influences on disease trends present an important research topic, because observed seasonal fluctuations in infection diseases reflect short-term weather influences. This should also be done in the frame of monitoring programs for livestock farming, taking climatological aspects into consideration.

In addition, data are needed on the role of meteorological parameters (e.g. temperature, heavy rainfall) in the survival of microorganism within the environment, crops, or food, and in their transmission to food in different geographical areas under natural conditions. These studies should also regard livestock because food-borne pathogens often originate from infected livestock animals besides humans. Furthermore, the role of overflow after heavy rainfall in the microbiological contamination of non-treated water sources is an additional topic for research. The combination of these different data may enable an estimate of potential changes in the incidence of water- and food-borne infection diseases under the conditions of climate change.

With the present knowledge, some precautionary measures may be applied in order to decrease potential risks (hazards) which may be the result of climate changes. For example, it is assumed that heavy rainfalls and the subsequent overflow of rivers and flooding might become more frequent in Europe (Downing et al., 1996; Nicholls and Mimura, 1999). Therefore we need both water treatment and efficient gullies and drain systems that take up the bigger amount of overflow to prevent the additional dissemination of contaminated water. Furthermore, the uptake of recreational water by swimmers should be avoided because water-borne bacteria could be transmitted in waters nearby agricultural areas.

4. Conclusions and recommendations

Climate change in the 21st century is a worldwide recognized issue for most regions of our planet, notwithstanding the fact that the causes of this change are still a matter of debate. The range of climatic and environmental parameters possibly being altered as a consequence of the climate change is quite wide and differs across the continents. Consequently, the related effects on food and feed chain may be different and should be studied on a regional basis. Even though geographical blocks will be involved in specific climatic changes leading to different problems in food and feed safety, impairment of food and feed safety in each area of the planet will likely affect other geographically diverse regions due to globalization.

Crop cultivation is recognized as a relatively susceptible part of the food and feed production sector that could be affected by climate change, but also livestock production could be heavily influenced. With regard to crop cultivation, variations in climatic parameters such as temperature, drought, precipitation, wind, and CO₂ levels are projected to have notable consequences on crops in terms of changes in the demand for fertilizer and pesticides, deterioration of the quality of soils, expanding ranges of crop pests and altered transmission dynamics of insects, pests and plant diseases. Also for livestock, both harmful and beneficial effects of climate change can be hypothesized, depending on the area and circumstances. For example, the impact of altered seasonal temperatures on productivity may be adverse if higher temperatures lead to decreased production of animal products (e.g. milk, meat) in summer but lead to better in-house livestock keeping and production conditions in winter.

Both chemical and microbiological risks are foreseen to impair food and feed safety as a consequence of climate change: in particular mycotoxins, marine biotoxins (phycotoxins), pesticide residues, trace metals and other chemicals could affect food and feed safety. Threats to food safety due to climate-change-related alterations in the levels of pathogenic micro-organisms present in food are also relevant. Most of these effects may be interrelated and should be faced through an interdisciplinary approach involving expertise from food science, environmental and climatic science, economic science, and trade. The modeling approach could aid the generation of mitigation and adaptation measures necessary to the risk managers for facing the emerging risks related to climate changes. For instance, for water-borne diseases, improved water treatment could diminish the effect of extreme weather in the future, since it is known that heavy rainfall events can contribute to water treatment failures.

Efforts should be devoted to individualize more precisely the consequences of different climatic scenarios on the related chemical and microbiological issues, in order to better identify adaptation and mitigation measures.

As in all activities of risk analysis, communication should play a prominent role regarding the consequences of climate changes on food and feed safety. Among stakeholders, awareness should be raised that climate-change-induced alterations in agriculture and manufacturing practices can pose new risks to food and feed production and therefore represent an issue in managing the consequences of climate change.

Due to the novelty of the issue, extensive work should be developed on the topic of climate change and potential implications for food safety, which includes:

- Developing models (on the basis of the available information and on the generation of reliable new data) in order to obtain more information on the spatial distribution of risk determinants for food systems under different scenarios of climate change;

- Assessing the possible impact of climate change on main categories of risks potentially affecting food and feed safety. This will require a multidisciplinary approach involving sciences of human and animal health, agriculture, meteorology, governmental policy, and socio-economics;
- Evaluating options for adaptation measures aimed at reducing vulnerability of food chain to climate change. The process should employ an “adaptation flow chain” involving scientists, managers, communicators, and stakeholders;
- Estimating cost-benefit ratios of the adaptation measures, taking into consideration that each sector of the food chain has its own specific needs and that higher cost-benefit ratios can be achieved if adaptation measures are implemented at an earlier stage.

Conflict of interest statement

All authors are professionals employed by the Italian National Institute for Public Health, RIKILT –Institute of Food Safety, the Catholic University of the Sacred Heart, the Dutch National Institute for Public Health and Environment, Alterra, Netherlands Environmental Assessment Agency, the University of Teramo, and the German Federal Institute for Risk Assessment, and as such do not have any interests that may conflict with the contents of the article above.

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